CONCRETE AT ELEVATED TEMPERATURE

by

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SYNOPSIS

A review of available literature shows that a large number of test variables may affect the properties of concrete at elevated temperature. This project is primarily concerned with the effect of heating time on the linear deformation and some structural properties of concrete and mortar heated under both fully saturated and drying conditions. The significance of microcracking, caused by incompatible thermal expansion of the mix constituents, is investigated, as well as the influence of the coarse aggregate on the property behaviour of heated concrete.

Ordinary Portland Cement of South African manufacture was used in this project. The fine aggregate was a natural siliceous sand (Fineness Modulus of 1,76), and the coarse aggregate was a crushed quartzite graded to -18,85 mm + 9,42 mm. A total of six mixes were used; three concrete mixes and three mortar mixes. The mortar mixes differed from the respective concrete mixes only in that they contained no coarse aggregate, i.e. for a particular mortar mix the ratio of water to cement, and fine aggregate to cememnt, was exactly the same as for the corresponding concrete mix. The ratio of water : cement : coarse aggregate : fine aggregate for the three concrete mixes were:

(i) 0,50; 1; 3,28; 2,08;

(ii) 0,58; 1; 3,28; 2,08;

(iii) 0,58; 1; 3,90; 2,42.

It was anticipated that from the concrete and mortar mixes corresponding to (ii) and (iii) above, an indication of the influence exerted by the volumetric concentration of aggregate on the properties of heated concrete would be obtained, and from the mixes corresponding to (i) and (ii) above, some insight into the effect of water/cement ratio on the property behaviour of heated concrete would be obtained.

The test specimens used were 273 x 76 x 76 mm plain concrete and mortar beams. Specimens were cured in a humidity room (100% relative humidity and 21 °C) for 27 days. On the 27th day the beams were removed from the humidity room and stored in water at 30 °C * until the heating test commenced the following day. A total of 24 specimens were used for heating at a particular test temperature.

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* This temperature was used as the datum for all expansion and shrinkage measurements.

The investigation was performed in two phases, viz:

(i) test specimens were allowed to dry at test temperatures of 70°C, 100°C, 150°C, 250°C and 400°C respectively;

(ii) test specimens remained fully saturated during heating at test temperatures of 70°C and 95°C.

Apart from the abovementioned differences in test procedure, the tests performed on specimens in the two respective phases of the investigation were exactly similar.

Specimens were heated to the required temperature at a rate of heating of 30°C/hr. During heating, and for the duration of the time that specimens were held at temperature, the deformational behaviour and weight loss of test specimens was continuously monitored. Immediately that the desired temperature was attained, three test specimens were removed from the furnace (from the water-bath for specimens which remained fully saturated during heating). Of these specimens, one was immediately tested in compression *. The other two specimens were slowly cooled to the datum temperature and the residual ** linear deformation, water loss, ultrasonic pulse velocity and dynamic Young's modulus determined. One of these specimens was tested in compression and the other specimen was re-immersed in water at 30°C for one week. After this period the same tests as were carried out prior to re-immersion in water were performed on the third specimen whereupon the specimen was tested in compression.

The above procedure was repeated on batches of specimens (i.e. three test specimens per batch) removed at 12-hourly intervals from the time when the maximum temperature was attained. After approximately 48 hours the specimens still remaining in the furnace (or waterbath) were all cooled to 30°C and then subjected to two temperature cycles. At each peak of the temperature cycle, batches consisting of three specimens were removed and tested as explained above.

It was found that the compressive strength, dynamic Young's modulus and ultrasonic pulse velocity of concrete and mortar test specimens which remained fully saturated during heating is reduced at temperatures of both 70°C

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* A modified compression test on the beam specimen.

** The linear deformation of test specimens after cooling to the datum temperature.

and 100°C. The reductions in these properties for test specimens made from the mortar mixes were usually greater than, or equal to, the reductions for specimens made from the concrete mixes. During the heating period the compressive strength of both mortar and concrete specimens increases whereas the ultrasonic pulse velocity and dynamic Young's modulus decrease. The linear expansion of test specimens also increases during the heating period and test specimens exhibit a residual linear expansion when cooled to the datum temperature. The above property changes are primarily associated with two chemical reactions which occur within saturated specimens at elevated temperature: the first reaction occurs within the cement paste only, and the second reaction is a chemical change which is related to the fact that both the coarse and fine aggregate contained a high proportion of S_iO_2. These chemical changes appear to be irreversible. There is no evidence that microcracking is a significant factor in the property reductions of saturated specimens at either 70°C or 100°C.

The experimental results for test specimens which underwent drying during heating fall into two categories, viz: test specimens which underwent drying at either 70°C, 100°C or 150°C, and test specimens which underwent drying at either 250°C or 400°C.

For both concrete and mortar test specimens which underwent drying at either 70°C, 100°C or 150°C, the compressive strength is lower than the compressive strength of unheated specimens. However, the compressive strength increases most significantly during the heating period: the compressive strength at the end of the heating period is never reduced by more than 4% of the unheated reference strength. In many instances the compressive strength increases to a value which is greater than the unheated reference strength. During the heating period the linear expansion of test specimens decreases progressively and a residual linear contraction occurs when test specimens are cooled to the datum temperature. The greatest residual contraction occurred for the respective concrete and mortar specimens cooled from 150°C. At test temperatures of 70°C, 100°C and 150°C the compressive strength after cooling specimens to the datum temperature is greater than the compressive strength of specimens tested whilst hot. The ultrasonic pulse velocity and dynamic Young's modulus is reduced for specimens cooled from either 70°C, 100°C or 150°C. The reductions in these properties become greater for specimens which were cooled at successive times during the heating period, despite the fact that the compressive strength increases for specimens tested at successive test times during the heating period.

The behaviour of compressive strength, linear deformation, dynamic Young's modulus and ultrasonic pulse velocity of test specimens cooled from either 70°C, 100°C or 150°C is primarily associated with the loss of capillary pore water and water from the gel pores. At these temperature levels there is no evidence of unstable crack propagation due to tensile stresses which accompany incompatible differential movement between the mix constituents. It is proposed that these stresses are relieved by creep of the cement paste: the creep having been facilitated by the presence of intercrystalline water between gel particles. The experimental results suggest, too, that upon re-immersion of specimens which were cooled from either 70°C, 100°C or 150°C, microcracking may be a significant factor influencing the structural properties of both concrete and mortar specimens. This is associated with irrecoverable contraction of the cement paste during the heating period. Upon re-immersion, swelling of the cement paste relative to aggregate causes large tensile stresses within the cement paste. These may be of sufficiently great magnitude to initiate unstable microcracks. This becomes apparent as a large reduction in compressive strength of both concrete and mortar specimens which were re-immersed in water.

The experimental results indicate that for test specimens which underwent drying at either 250°C or 400°C the compressive strength, dynamic Young's modulus and ultrasonic pulse velocity are always reduced. For both concrete and mortar specimens tested at the successive test times during the heating period, these properties usually exhibit progressively greater reduction. The residual linear deformation of both concrete and mortar test specimens cooled from 250°C is a contraction. However, this contraction is not as large as the contraction which occurred for specimens cooled from 150°C. The residual linear deformation of both concrete and mortar specimens cooled from 400°C was an expansion; the expansion increases for specimens cooled at the successive test times during the heating period. The values of Poisson's ratio for specimens cooled from either 250°C or 400°C are lower than the values of Poisson's ratio for unheated reference specimens. These values of Poisson's ratio increased for successive tests during the heating period; for specimens cooled from 400°C the values of Poisson's ratio became greater than the value of Poisson's ratio for unheated specimens.

The structural behaviour of test specimens which underwent drying at either 250°C or 400°C is thought to be influenced to a large extent by unstable propagation of microcracks. The cracking occurs due to tensile stresses which are caused by:

(i) the contraction of cement paste relative to aggregate particles during the loss of non-evaporable water (during the heating period),

(ii) the difference between the coefficient of thermal expansion of the concrete or mortar constituents (during cooling).

It appears that at temperatures above 150°C, the ability of the cement paste to relieve these stresses by creep is sharply curtailed by the fact that the microstructure of the paste is fixed predominantly by solid-solid bonding.

For test specimens which underwent drying during heating it was also found that the property changes which occur for test specimens made from the mortar mixes are usually greater than, or equal to, the property changes which occur for test specimens made from the concrete mixes. The exception to this is the dynamic Young's modulus of test specimens cooled from 400°C: concrete test specimens exhibit greater reduction than mortar test specimens.

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INTRODUCTION

Concrete is a material which could effect a considerable economy in the construction of both primary and secondary containment structures of nuclear reactors. From the point of view of radiation shielding, concrete is well suited to the abovementioned applications. This is because the chemical composition of concrete includes both light and heavy elements; concrete is thus a good attenuator of both neutrons and gamma radiations.

However, certain structural properties of concrete are adversely affected by temperatures of the order of those which may be encountered in the primary containment structure of a nuclear reactor. It is, therefore, current practice to provide costly cooling systems to limit the temperature to which the concrete is exposed. If it could be ascertained that concrete may be used at higher temperatures, a considerable saving in the overall cost of primary containment could be effected. Also, despite the fact that biological shields are not normally subjected to particularly high temperatures, the properties of the shielding concrete are required to be known for the fail-safe design of shields.

Investigators do not always agree as to why certain structural properties of concrete are adversely affected by elevated temperature, and to what extent factors like mix proportions; cement type; aggregate type; curing history; may influence the structural properties of heated concrete. The difference in opinions could be partly attributed to the fact that the test methods and testing procedures for concrete at elevated temperatures are not standardized. Consequently, the difference in test methods and procedures makes comparisons between the experimental results of different investigators difficult, i.e. it is not possible to establish conclusively from these studies the reasons for the deterioration in certain of the structural properties of heated concrete.

In the reviewed literature regarding the testing of concrete properties at elevated temperature, it is apparent that the various investigators did not always use the same heating time. In some instances tests were performed immediately that the desired temperature level was attained, while in other instances the test specimens were maintained at the test temperature for periods which ranged from a few hours to a few days. It is thought that the different heating times adopted by the various investigators could be partly responsible for the wide variation between reported results, as well as for

the differences of opinion regarding the factors which influence the structural behaviour of heated concrete.

The effect of heating times becomes clear when it is realised that: for specimens which remain fully saturated during heating, the stresses which result from incompatible differential expansion of the constituents may be relieved by creep; for test specimens which are allowed to dry during heating, the stresses which result from either differential expansion, or from contraction of cement paste relative to aggregate, may be relieved by creep, or progressive microcracking may occur within the concrete. Also, it should be remembered that time dependent chemical reactions may occur within the concrete during the heating period at a particular temperature. The chemical reactions may be of a beneficial nature, e.g. heat stimulated cement hydration, or reactions which may be detrimental to the structural properties, e.g. the conversion of existing hydrates to hydrates of lower strength. These reactions may be of particular importance in instances where sufficient water is available for reaction, e.g. in sealed concrete, and in unsealed concrete at temperature levels where the removal of evaporable water is relatively slow.

From the reviewed literature it is also apparent that, in much of the research, the reduction in the structural properties of concrete is attributed to either weakening, or failure, of the bond at the mortar/coarse aggregate interface as a result of stresses which accompany incompatible thermal expansion of these constituents. The investigators do not take into consideration the fact that stresses at the cement paste/fine aggregate interface may have been responsible for the deterioration of structural properties.

The purpose of the following investigation is to determine for both specimens which remain fully saturated and for specimens which are allowed to dry;

(i) the effect of heating time on the linear deformation and some physical properties of concrete and mortar test specimens heated to various temperature levels,

(ii) whether microcracking within test specimens is a significant factor in affecting the structural behaviour of heated concrete and mortar test specimens, and

(iii) whether the coarse aggregate phase in concrete is necessarily detrimental to the structural behaviour of heated concrete.

PART I

REVIEW OF LITERATURE

CHAPTER 1 : THE EFFECT OF ELEVATED TEMPERATURE ON SOME STRUCTURAL PROPERTIES OF CONCRETE

1.1 Compressive Strength

The compressive strength of heated concrete has been the most widely investigated structural property. The general tendency is for the compressive strength to decrease when concrete is heated: the higher the temperature the greater the reduction in compressive strength. In Fig. I.1 some compressive strength data[2,5,7,18] are summarized and the percentage strength retained after heating plotted against temperature. The percentage strength retained is the ratio of the heated compressive strength to the unheated compressive strength of a similar test specimen. This ratio is hereafter referred to as the residual ratio. The mean of the data at various temperature levels has been calculated and is shown. Though the mean has no statistical significance, it does indicate that, in general, the compressive strength decreases as the test temperature increases.

Some of the research[3,17], however, indicates that an increase in compressive strength may occur at certain temperatures, i.e. an increase with respect to the reference strength at room temperature. This is thought to be due to the fact that the loss of evaporable water occurred during heating. In these investigations[3,17] an initial decrease in compressive strength of up to 30 per cent was observed at temperatures below 100°C. At 200°C - 300°C the strength in some cases became greater than the strength of an unheated reference specimen. Loss in strength was again apparent above 300°C, with no subsequent recovery at higher temperatures.

The compressive strength of specimens sealed to prevent moisture loss during heating is more adversely affected than the compressive strength of specimens which undergo water loss during heating. This is illustrated by the data of Lankard[1] in Fig. I.2. The differences between the percentage compressive strengths retained after heating sealed and unsealed specimens are readily apparent. Particularly noticeable is the fact that sealed specimens undergo greater reduction in compressive strength than unsealed specimens. In this respect it is worth noting that the same

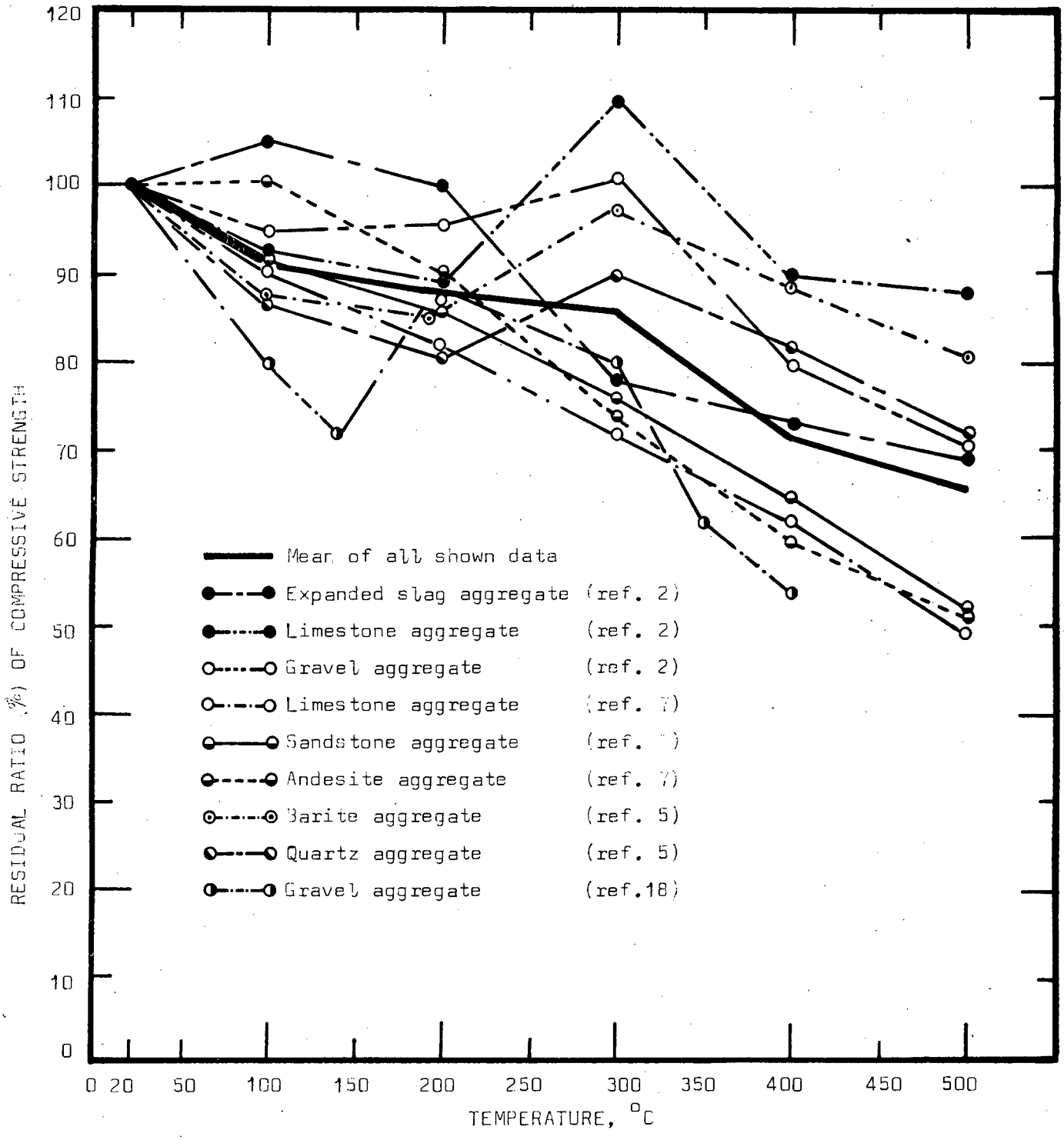


FIG. I.1: The effect of elevated temperature on the compressive strength of concrete as studied by various investigators. (Ordinary Portland cement only.)

research worker[1] found that it is not possible to predict the behaviour of sealed specimens from the behaviour of similar, but unsealed specimens.

Compressive strength reductions are reported[1,3,4,8,16,17] to be further aggravated by repeated thermal cycles. The effect of cycling on the compressive strength of concrete incorporating two different aggregates is shown in Fig. I.3. It is apparent that a progressive loss of compressive strength occurs as the number of thermal cycles is increased. However, the major part of the strength loss is incurred in the first five cycles. The authors[3,4,8,17] attribute these results to dimensional changes causing fracture of the bond between the aggregate and mortar matrix.

Attempts to manufacture concretes less susceptible to reduction in compressive strength due to heating, have been only partly successful; complete insensitivity of compressive strength to temperature has not been achieved. Crispino[8] developed a concrete using ordinary Portland Cement and barite aggregate (B.H.T. concrete); the choice of barite as aagregate was based on the compatibility of the coefficient of thermal expansion of the aggregate with that of the mortar matrix, approximately 12×10^{-6}/deg C and 14×10^{-6}/deg C respectively. This concrete was compared to a standard concrete incorporating limestone aggregate with a coefficient of thermal expansion of $6{,}5 \times 10^{-6}$/deg C. It was found that the reduction in the compressive strength of B.H.T. concrete after 6 thermal cycles to 500°C, was less than that of the standard concrete after the 6 cycles to a maximum temperature of 350°C. However, the loss in compressive strength of the B.H.T. concrete was not completely eliminated.

1.2 Flexural Strength

The flexural strength of concrete at all temperatures up to 500°C follows a roughly similar pattern to that exhibited by the compressive strength. However, flexural strength tends to be more sensitive to the heat exposure than compressive strength, i.e. the reductions in flexural strength are usually more severe than those incurred in compression. Data[2] illustrating this are shown in Figs. I.4 and I.5; the residual ratios of compressive strength and transverse strength, respectively, plotted against temperature. It is apparent that the flexural strength does not indicate a similar tendency to increase at certain temperatures (with reference to the control strength) as was observed under some conditions with the compressive strength.

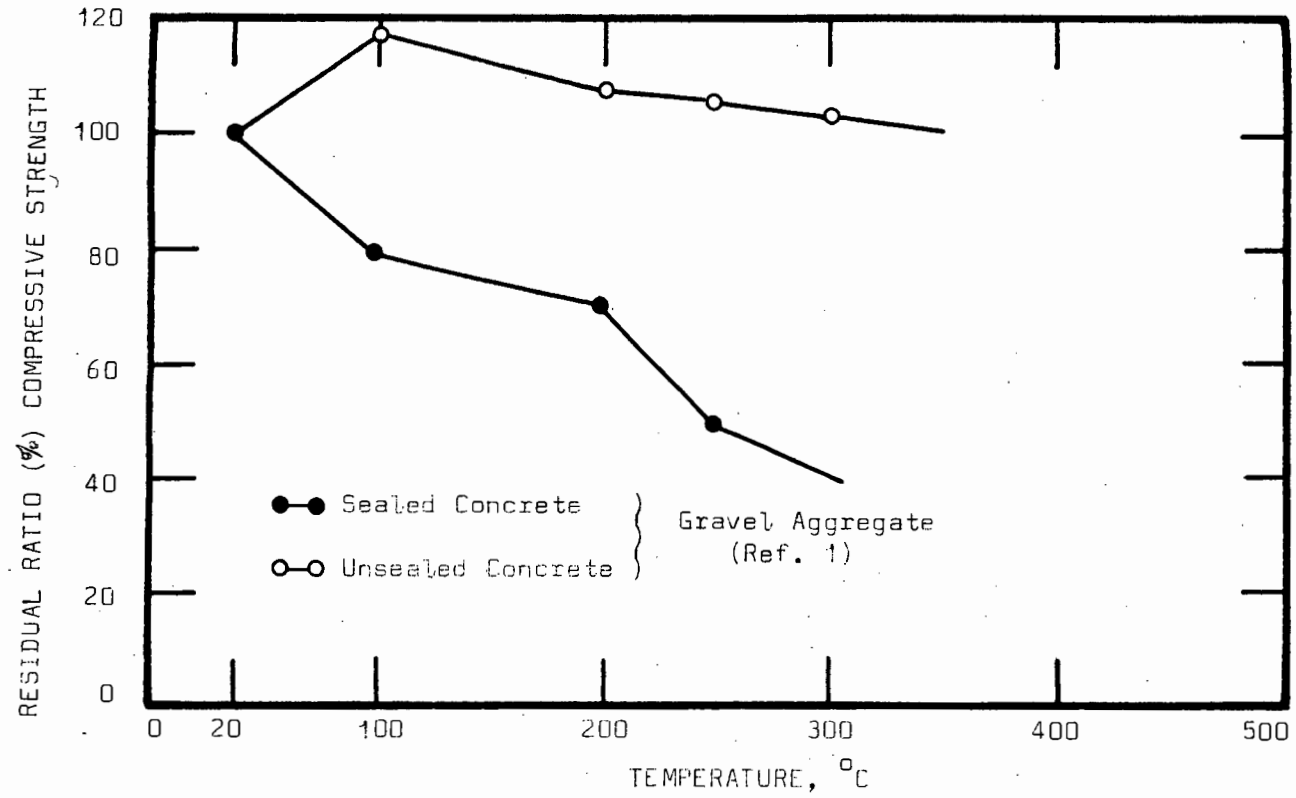


FIG. I.2: The effect of elevated temperature on the compressive strength of sealed and unsealed concrete.

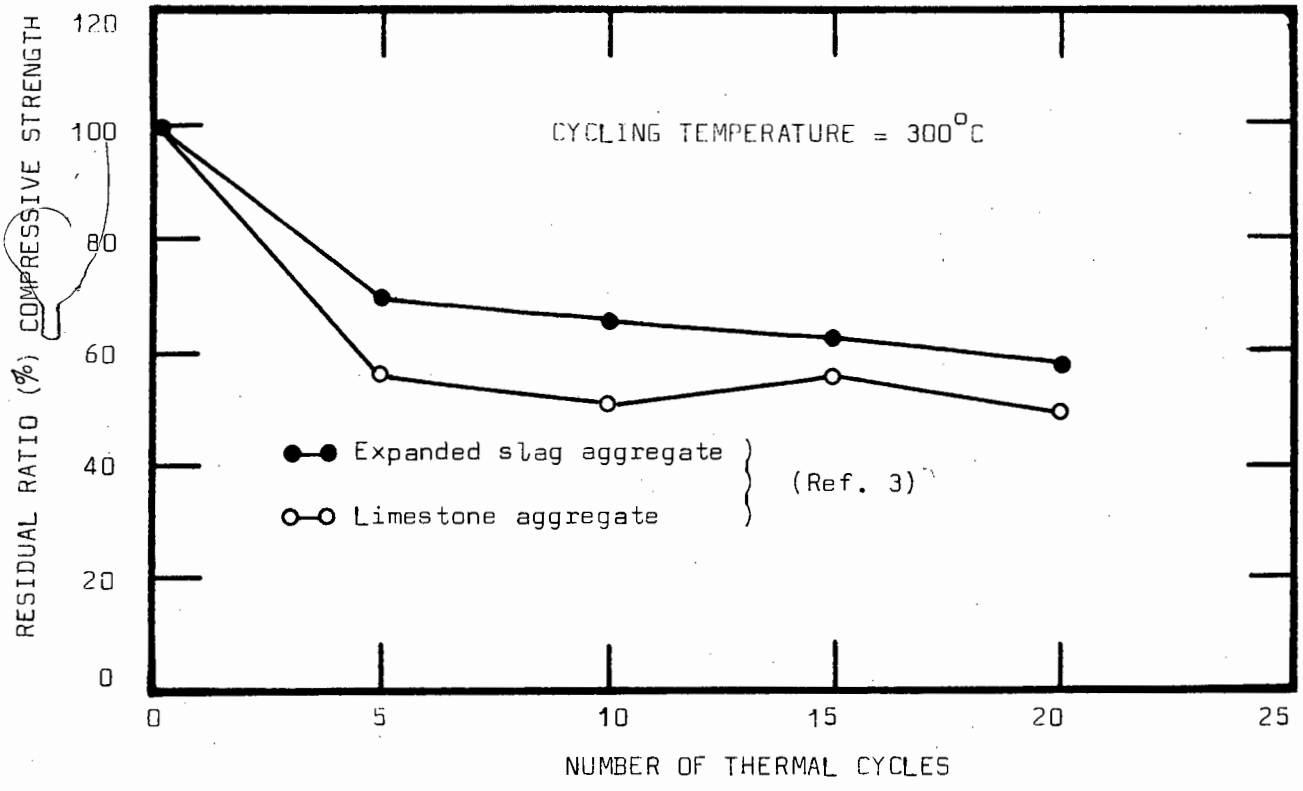


FIG. I.3: The effect of cycling on the compressive strength of unsealed concrete.

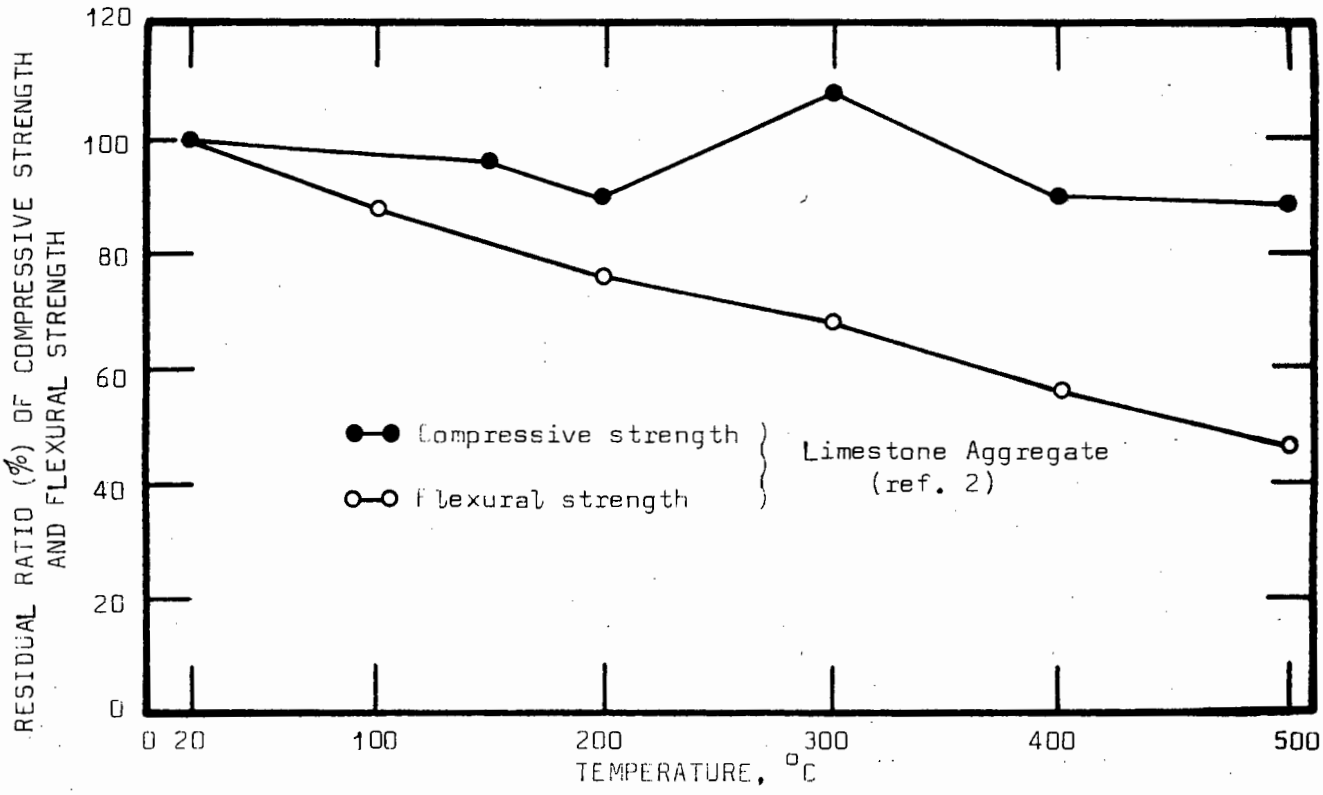


FIG. I.4: The effect of elevated temperature on the compressive and flexural strength of unsealed concrete made with limestone aggregate.

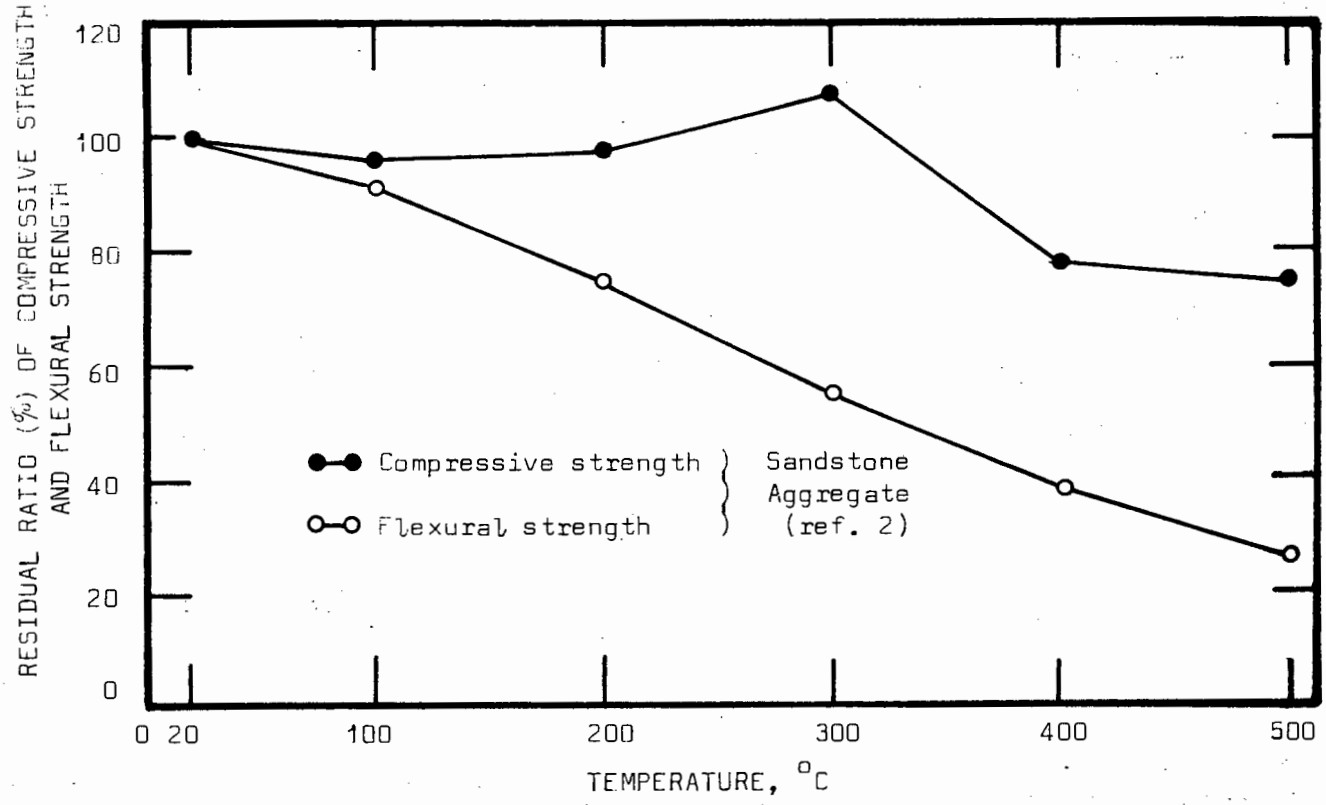


FIG. I.5: The effect of elevated temperature on the compressive strength and flexural strength of unsealed concrete made with sandstone aggregate.

Partial recovery of flexural strength, however, after an initial decrease at temperatures below 100°C, has been reported[18].

The difference between the behaviour of concrete tested in the dry state and concrete tested in the fully saturated states is also evident for the transverse strength of heated concrete. Data by Lankard[1] illustrating this are shown in Fig. I.6. It should be noted though, that these results are for flexural tests after the specimens had cooled from the treatment temperature. This could be a further possible cause for the variation between the two testing conditions.

Thermal cycling of specimens is found to aggravate the reduction of flexural strength at a given temperature[3,8,17]. The effect of cycling on the flexural strength of two concretes is shown in Fig. I.7. The data[3] are for concrete incorporating limestone and expanded shale-clay aggregate respectively, with maximum cycling temperature of 300°C. It is of interest to note that most of the reduction of flexural strength occurs within the first five thermal cycles.

1.3 Young's Modulus

The modulus of elasticity of concrete is always reduced when concrete is heated. Residual values of Young's modulus (both static and dynamic) as low as 15 percent of the unheated reference value are not uncommon at 500°C[7]. In general, the Young's modulus of concrete subjected to heat exposure is reduced more than either the compressive strength or the flexural strength. In Fig. I.8 the effect of elevated temperature on the Young's modulus of concrete made with limestone aggregate[7] is shown. Also shown are the residual ratios of compressive strength and transverse strength to indicate the relative performance of these three properties. In this regard, it is particularly interesting to note that Lankard[1] found the reductions in Young's modulus to occur despite increases in the compressive strength of unsealed concrete specimens at certain temperatures.

Repeated cycles of heating usually cause further reductions in Young's modulus[3]. Fig. I.9 illustrates how the residual value of Young's modulus varies with the number of thermal cycles to a temperature of 300°C. These data[3] exhibit the trend usually encountered with thermal cycling, viz. the maximum property reduction occurs within the the first 5 cycles.

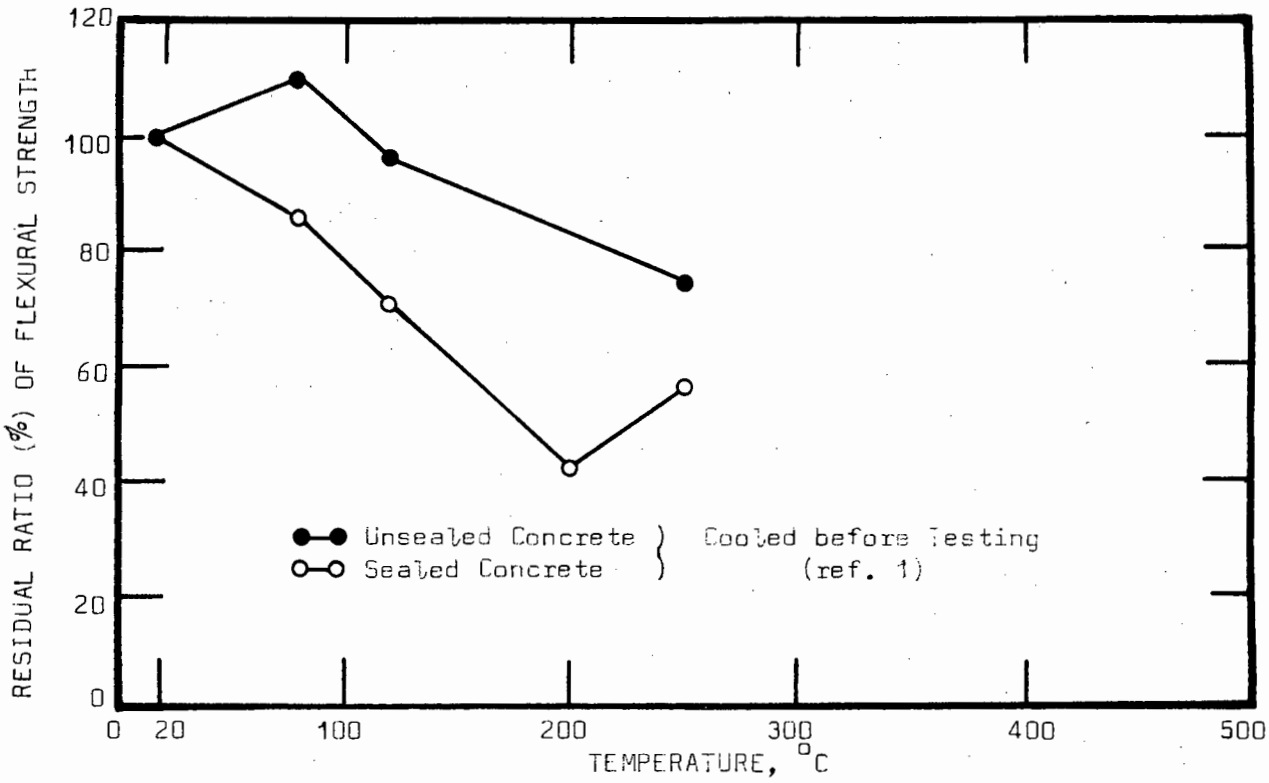


FIG. I.6: The effect of elevated temperature on the flexural strength of sealed and unsealed concrete.

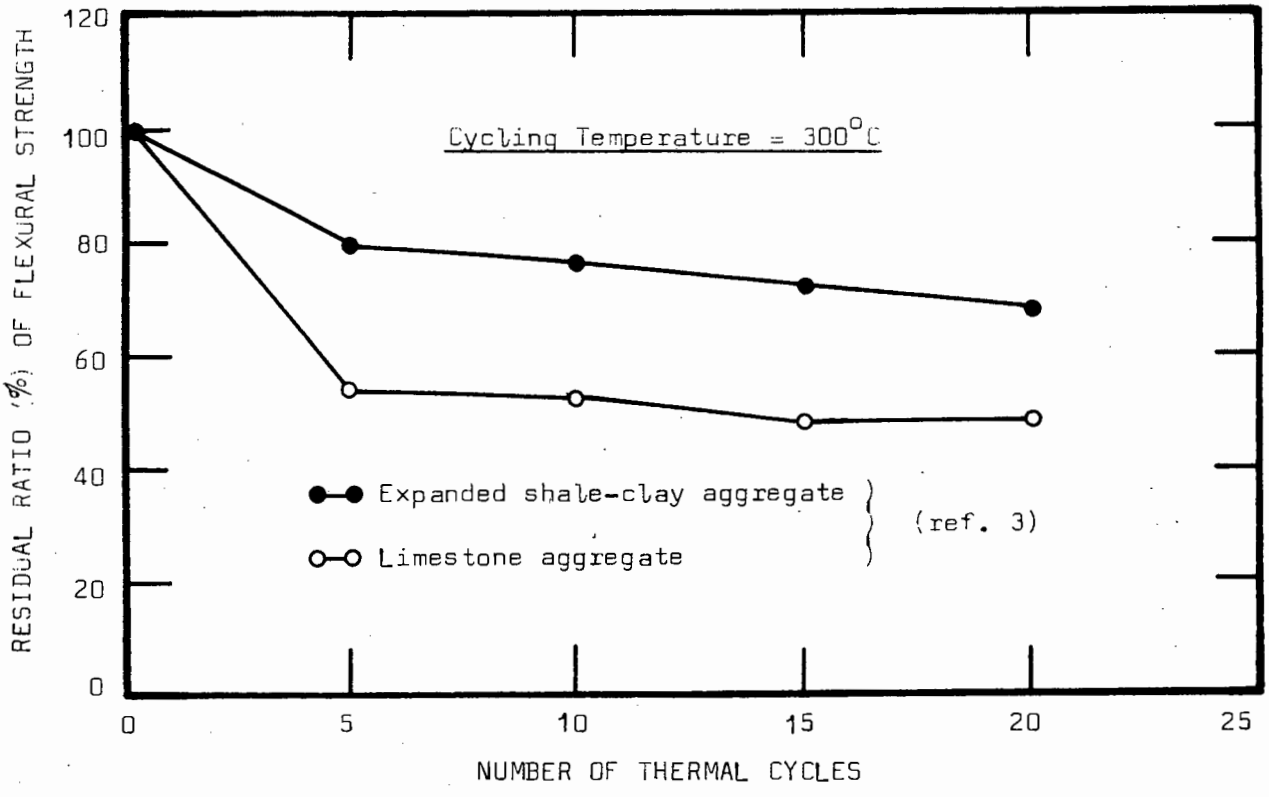


FIG. I.7: The effect of thermal cycling on the flexural strength of unsealed concrete.

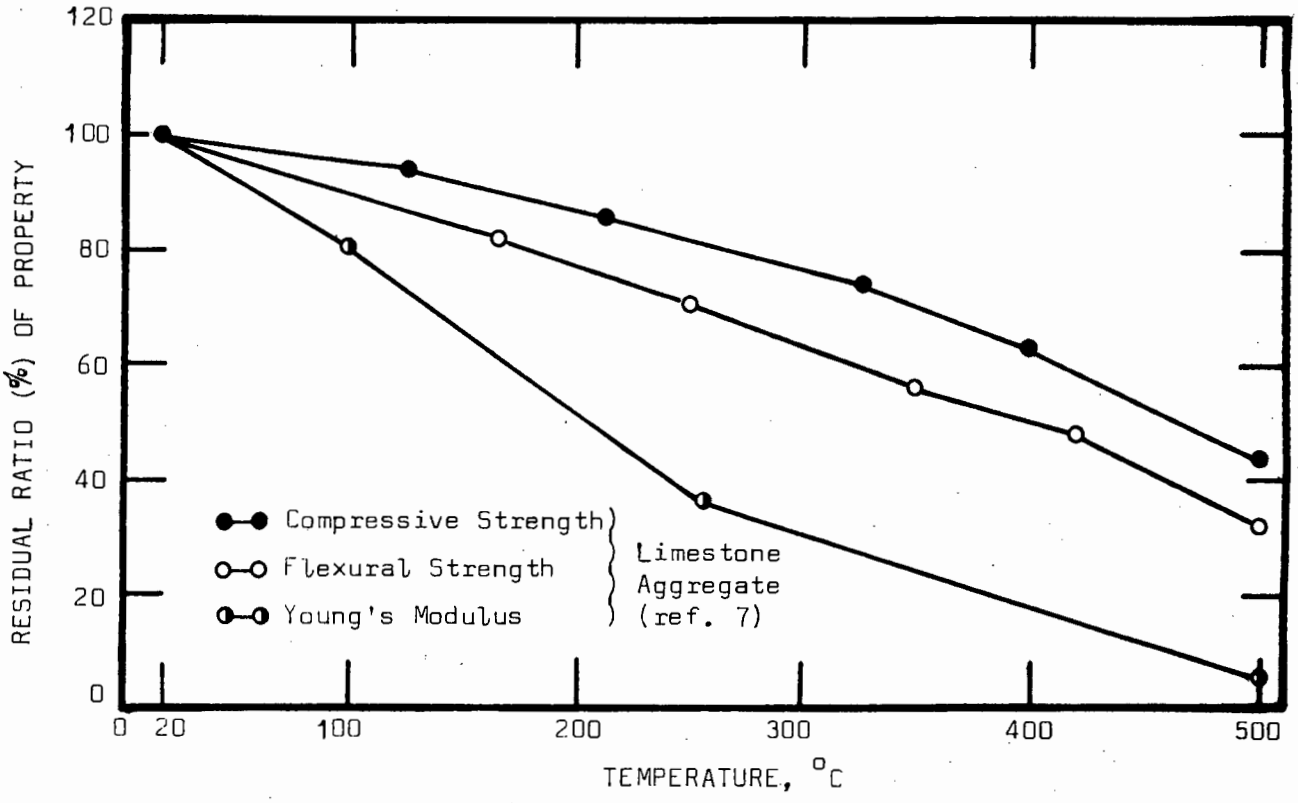


FIG. I.8: The effect of heating on Young's modulus, compressive strength and flexural strength respectively.

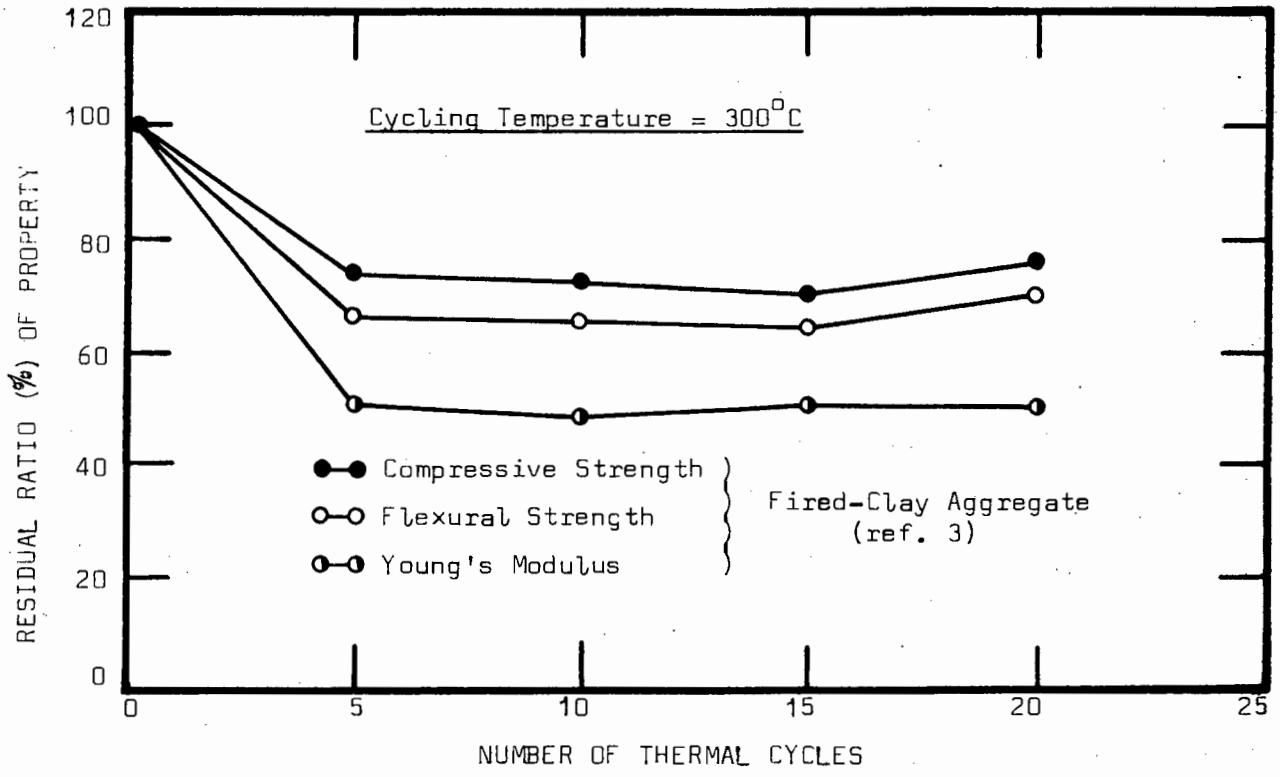


FIG. I.9: The effect of thermal cycling on Young's Modulus, compressive strength and flexural strength respectively.

The behaviour of Young's modulus in unsealed specimens is thought[1] to be related largely to the absence of the evaporable water at time of testing. Loss of evaporable water constitutes the removal of an incompressible phase. Solid surfaces, formerly in contact with elements of water, move closer together when load is applied. Consequently, the Young's modulus is reduced. This is probably the reason why concretes which have been designed to withstand reduction in compressive strength, nevertheless exhibit decreases in Young's modulus, e.g. the B.H.T. concrete developed by Crispino[8]. This concrete showed a 70 percent loss of Young's modulus after six heating cycles to 500°C; most of the deterioration having occurred in the first cycle.

Specimens sealed to prevent water migration during heating are also found to undergo deterioration of Young's modulus. In this case the relatively incompressible phase is totally retained within the concrete during heating. According to Lankard[1], the reduction of Young's modulus under these conditions is due to changes taking place in the mineralogical phase assemblage of the hydrated cement, i.e. a chemical change within the hydrated cement, which results in the formation of a physically weaker matrix. However, this has not been conclusively proved.

1.4 Poisson's Ratio

The Poisson's ratio of concrete subjected to heating has not been extensively investigated. At normal temperatures concrete has a Poisson's ratio of 0,15 to 0,20 when determined from strain measurements[30]. Dynamic determination of Poisson's ratio yields slightly higher values, with an average of approximately 0,24[11].

Philleo[29] reports that the Poisson's ratio (determined dynamically) of unsealed concrete specimens decreases as the testing temperature increases. The same author[29] indicates that the results of Poisson's ratio determined by the dynamic method are very erratic. This is because Poisson's ratio is sensitive to errors in determining the resonant frequencies; 1 percent error in frequency may result in a 20 percent error in Poisson's ratio.

The influence of elevated temperature on the Poisson's ratio (determined from strain measurements) or unsealed concrete made with quartzite aggregate

is reported by Marechal[13]. The results are plotted in Fig. I.10. It is apparent that there is a general tendency for Poisson's ratio to decrease as the temperature increases. At the maximum test temperature of 400°C, Poisson's ratio is less than half the value of Poisson's ratio before heating.

Results which do not conform to the abovementioned trend are reported by Crispino[8] for both a limestone aggregate concrete and barite aggregate concrete. Poisson's ratio was determined from strain measurements on unsealed concrete specimens after they had cooled to room temperature. It was found that at 110°C both the concretes tested had lower Poisson's ratio values than at room temperature. However, at higher temperatures (300° to 500°C) the Poisson's ratio increased, i.e. increased w.r.t. the value of Poisson's ratio of an unheated specimen. In general, the higher the temperature the greater the increase in Poisson's ratio. Crispino[8] attributes the increase in Poisson's ratio to microcracking of the concrete.

The effect of temperature on the Poisson's ratio of sealed concrete specimens was investigated by Nishizawa and Okamura[12]. The test temperatures were 40°C, 70°C and 90°C respectively; specimens having been maintained at these temperatures for periods ranging from 1 week to 13 weeks. It was found that the Poisson's ratio was not at all influenced by this thermal treatment.

With regard to the behaviour of Poisson's ratio it is worth noting some general comments by Neville[30]. If concrete is subjected to an increasing compressive load "the volumetric strain first decrease i.e. the effect of a monotonically increasing compressive stress is a densification of the concrete. However, at some point, the rate of change of volume becomes zero and hereafter an increase takes place. The point of change heralds the development of cracking to such an extent that the concrete is strictly speaking no longer a continuous body." It is, therefore, possible that the reported increases in the Poisson's ratio of concrete at certain temperatures, are caused by internal microcracking.

1.5 Ultrasonic Pulse Velocity

The pulse velocity is not a structural property of concrete. However, it is related to:

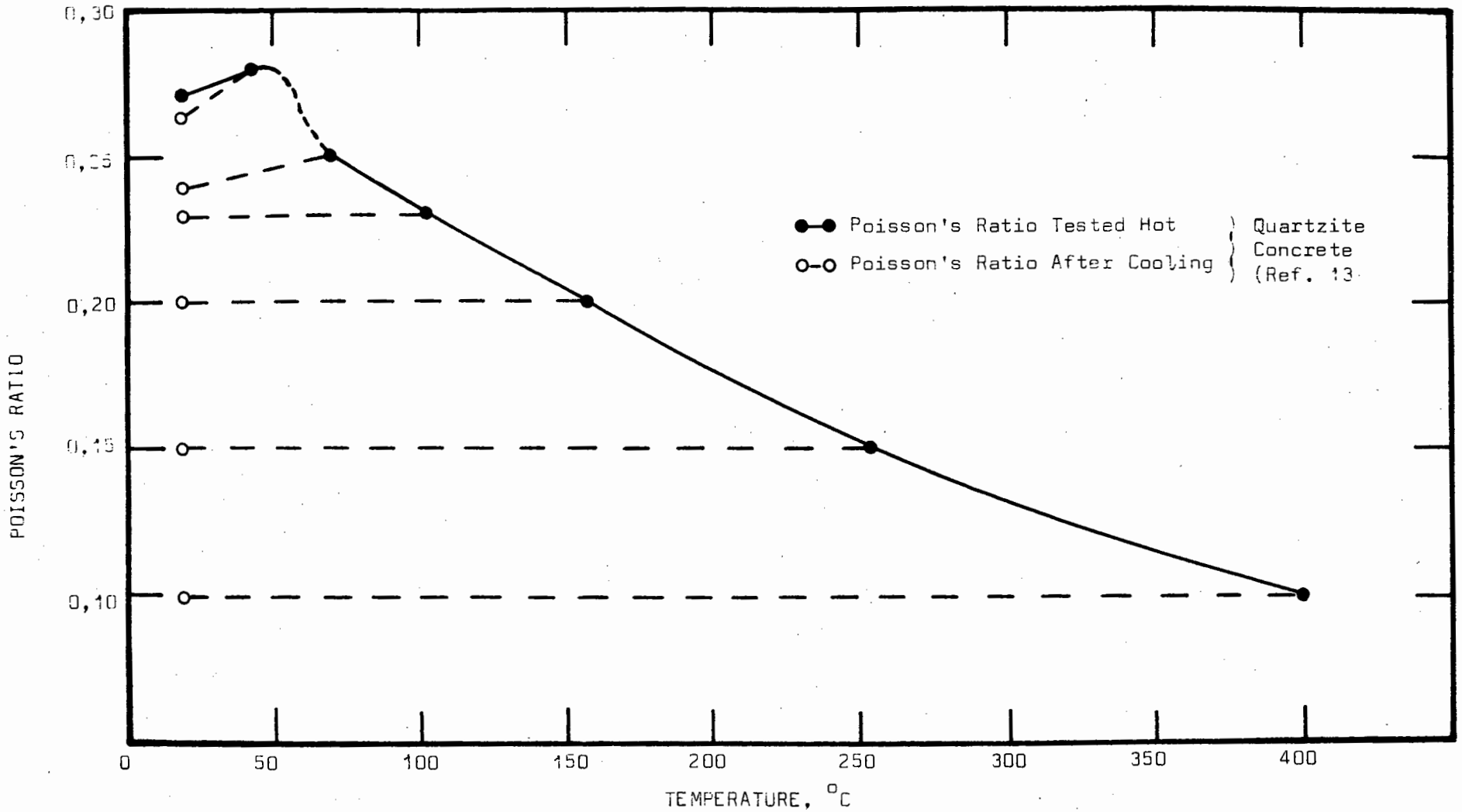


FIG. I.10: The effect of heating on Poisson's Ratio of quartzite concrete.

(i) Compressive strength - generally the greater the compressive strength the higher the pulse velocity[15,19]; and

(ii) Poisson's ratio, by the equation

$$\frac{KV^2}{E}\rho = \frac{1-\mu}{(1+\mu)(1-2\mu)}$$

where μ = Poisson's ratio
V = Pulse velocity
E = Dynamic Young's modulus
ρ = Density of the concrete
K = A constant, determined by the unit of measurement.

Being a non-destructive type of test, the pulse velocity is particularly useful for assessing the behaviour of concrete under adverse environmental conditions, e.g. elevated temperature. Care should be taken in interpreting the results though, since the pulse velocity is dependent on moisture loss, i.e. a decrease in pulse velocity occurs as concrete loses water. This decrease in pulse velocity should not be misconstrued as being indicative of microcracking within the concrete.

Zoldners[2] determined the reductions in pulse velocity when heating concretes made with gravel, limestone and sandstone aggregates respectively. The data are illustrated in Fig. I.11. These results indicate that at 700°C the pulse velocity can be reduced to 20 percent of the value determined at room temperature before heating. The question arises as to what extent the reductions in pulse velocity are caused by water loss and microcracking respectively. A possible method of determining this, may be by re-saturating the concrete by immersion in water. These results will not indicate the true extent of microcracks as the cracks themselves are filled with water. However, it may provide some indication of the extent of microcracking.

1.6 Creep

The creep of concrete at elevated temperatures follows the same general pattern as creep at room temperatures, viz. it is approximately an exponential function of the time under load, and a reasonably linear function of the applied stress (at least up to stress/strength ratios of 0,50).

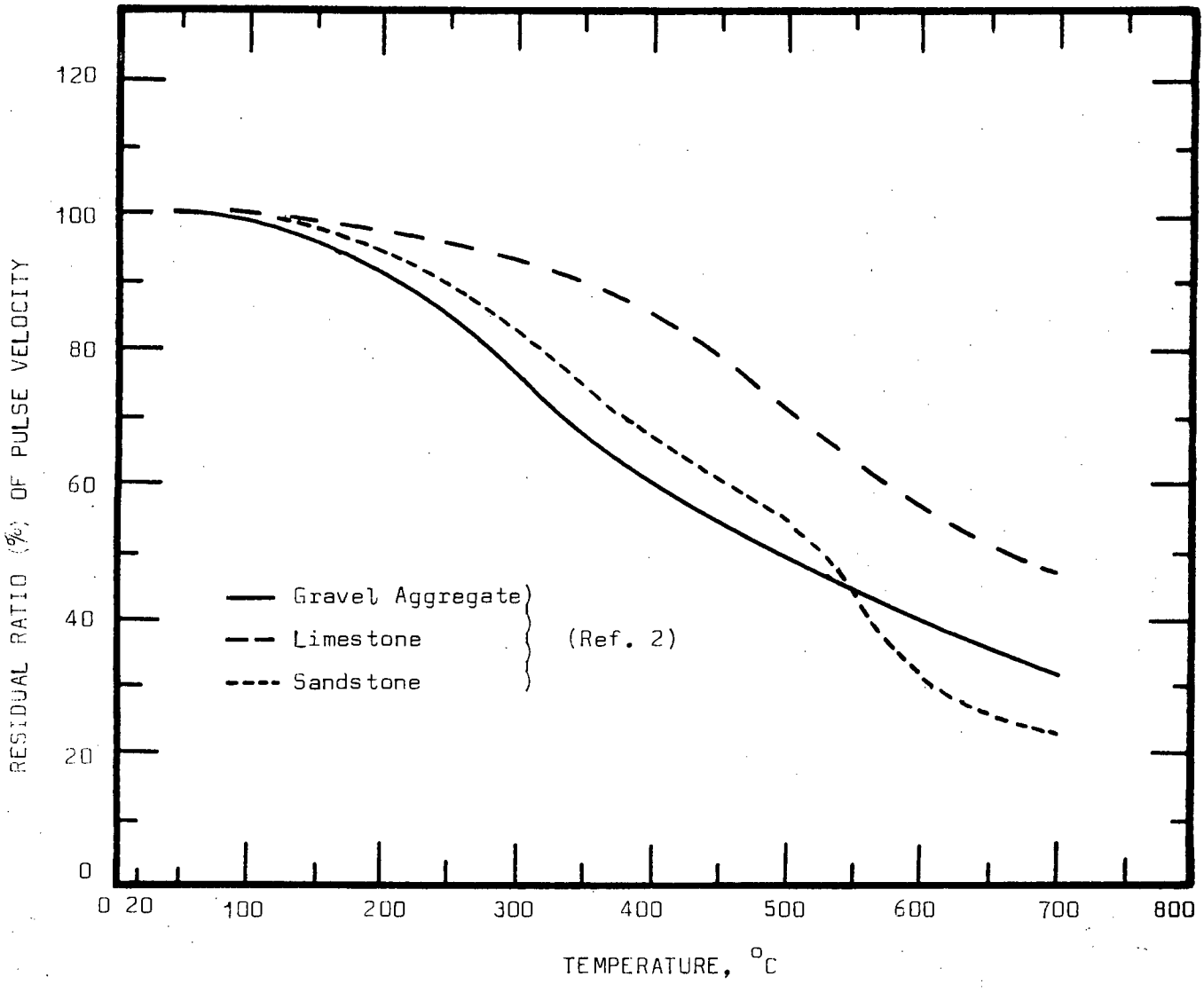


FIG. I.11: The effect of elevated temperature on the Pulse Velocity of concrete incorporating gravel, limestone and sandstone aggregate respectively.

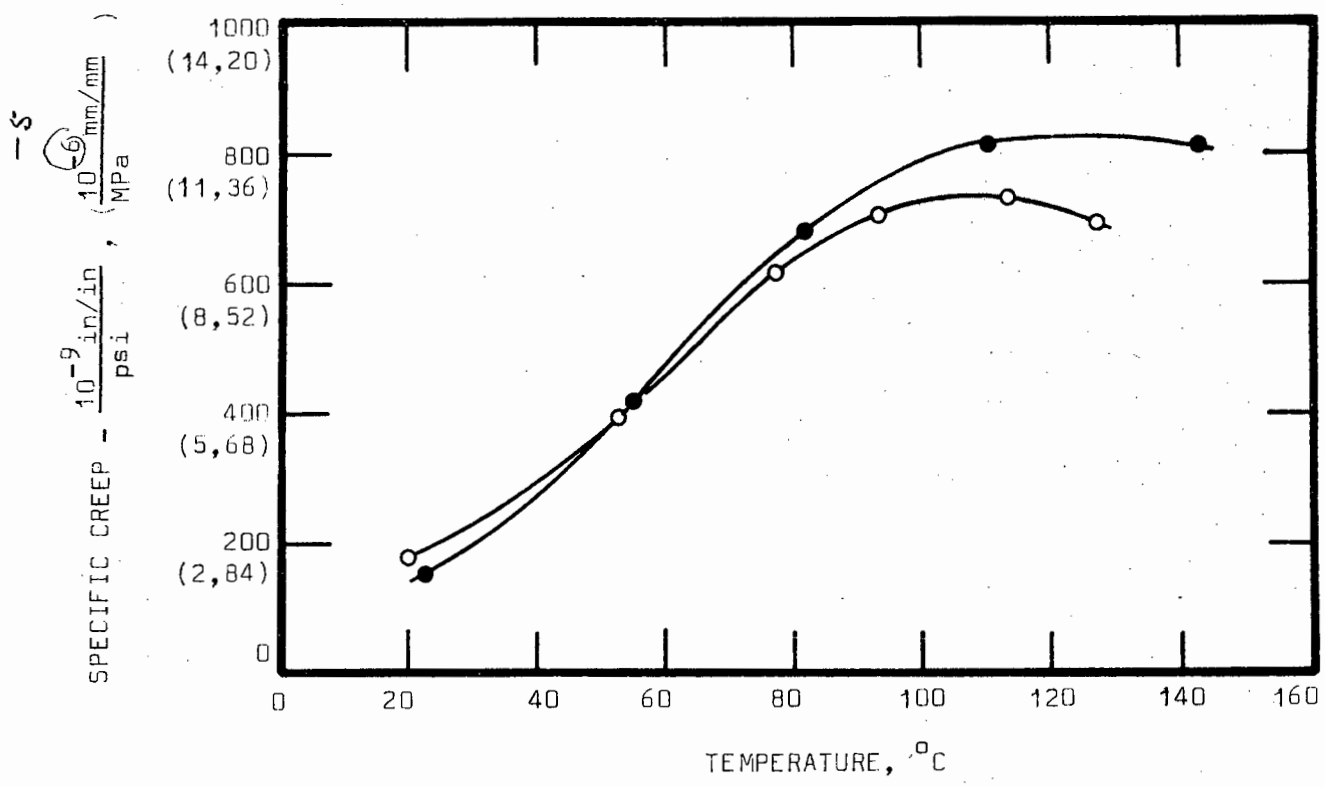
From the reported literature it appears that sealed (or water-stored) concrete specimens exhibit less creep than unsealed specimens. However, this cannot be stated with certainty as many of the reported results are not directly comparable. Creep values at various temperatures, as found by England and Ross[62], are illustrated in Fig. I.12. These results are for concrete loaded at 10 days to a stress/strength ratio of 0,20. It should be noted that for the sealed concrete the creep at 80 days of loading is plotted, whereas for unsealed concrete the data are for 60 days loading. From these results it appears that sealed specimens exhibit less creep than unsealed specimens.

In Fig. I.13 some further results[59,60,61,62,63,64] of creep determinations on sealed and unsealed specimens are plotted against temperature. In each case the experimental variables which could have affected the results are given, viz. whether the concrete was sealed or unsealed; the stress/strength ratio; the age at loading; the concrete compressive strength; the loading age at which the data was determined. It appears that, in general, concrete which is sealed exhibits less creep than unsealed concrete.

From Fig. I.13 it is apparent that the specific influence of elevated temperature is to increase the creep of concrete; the creep at 50°C being approximately two to three times as great as creep at room temperature. For temperatures from 50°C to 100°C, some controversy exists about whether there is a further increase of total creep. Some investigators[56,59,64] report a definite maximum of total creep in the range 50°C to 80°C and a corresponding minimum at temperatures around 100°C. (See Fig. I.13). However, other investigators are of the opinion that the creep of concrete increases with temperature up to around 100°C; the creep at 100°C at the end of a 60 to 100 day loading period being of the order of four to six times as great as the creep at room temperature[60,61,62,63]. Few data are available for the creep of concrete at temperatures exceeding 100°C.

The results of Marechal[66] for the creep of unsealed specimens at temperatures of 105°C, 150°C, 250°C and 400°C are plotted in Fig. I.14. It is apparent that in this range of temperature the magnitude of total creep increases as the temperature increases; at 400°C the creep may be as much as an order of magnitude greater than the creep at 20°C.

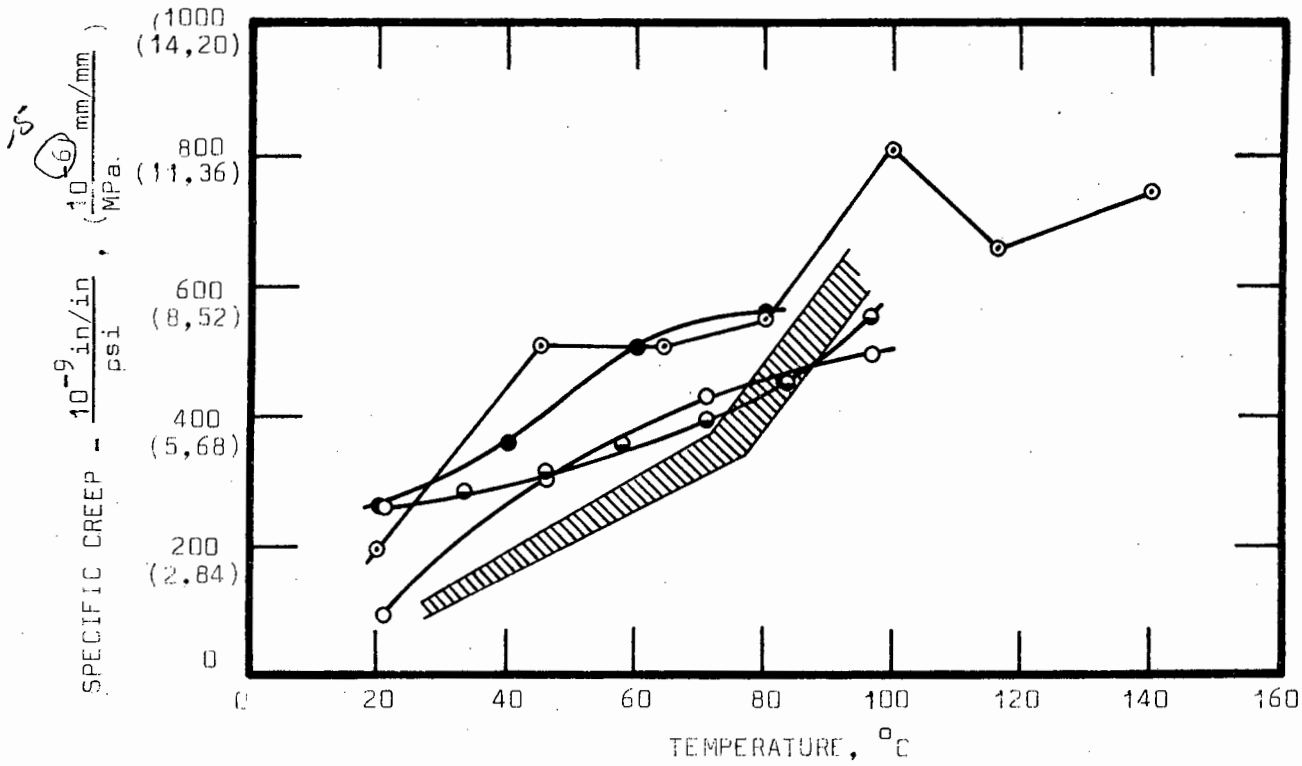
Contrary to the above difference in opinions regarding the total creep maximum at between 50°C and 80°C, most investigators[59,60,61,62,63,64,66]



England and Ross[62]. Loaded at 10 days to f/f_c' of 0,20; creep determined after 60 days of loading.

England and Ross[62]. Loaded at 10 days to f/f_c' of 0,20; creep determined on sealed specimens after 80 days of loading.

FIG. I.12: The specific creep of sealed and unsealed concrete specimens at various temperatures.



Nasser and Neville[59]. Loaded at 14 days to f/f_c' of 0,35; creep determined on sealed specimens after 90 days of loading.

Hannant[60]. Loaded at 6 months to f/f_c' of 0,20; creep determined on sealed specimens after 80 days of loading.

Arthanari and Yu[61]. Loaded at 15 days to f/f_c' of 0,20; creep determined after 60 days of loading.

Hickey[63]. Loaded at 60 days to f/f_c' of 0,10; creep was determined after 107 days of loading.

Nasser and Neville[64]. Loaded after 1 year water storage to f/f_c' of 0,45; creep determined after 90 days of loading under water.

FIG. I.13: The specific creep of sealed and unsealed concrete specimens at elevated temperature.

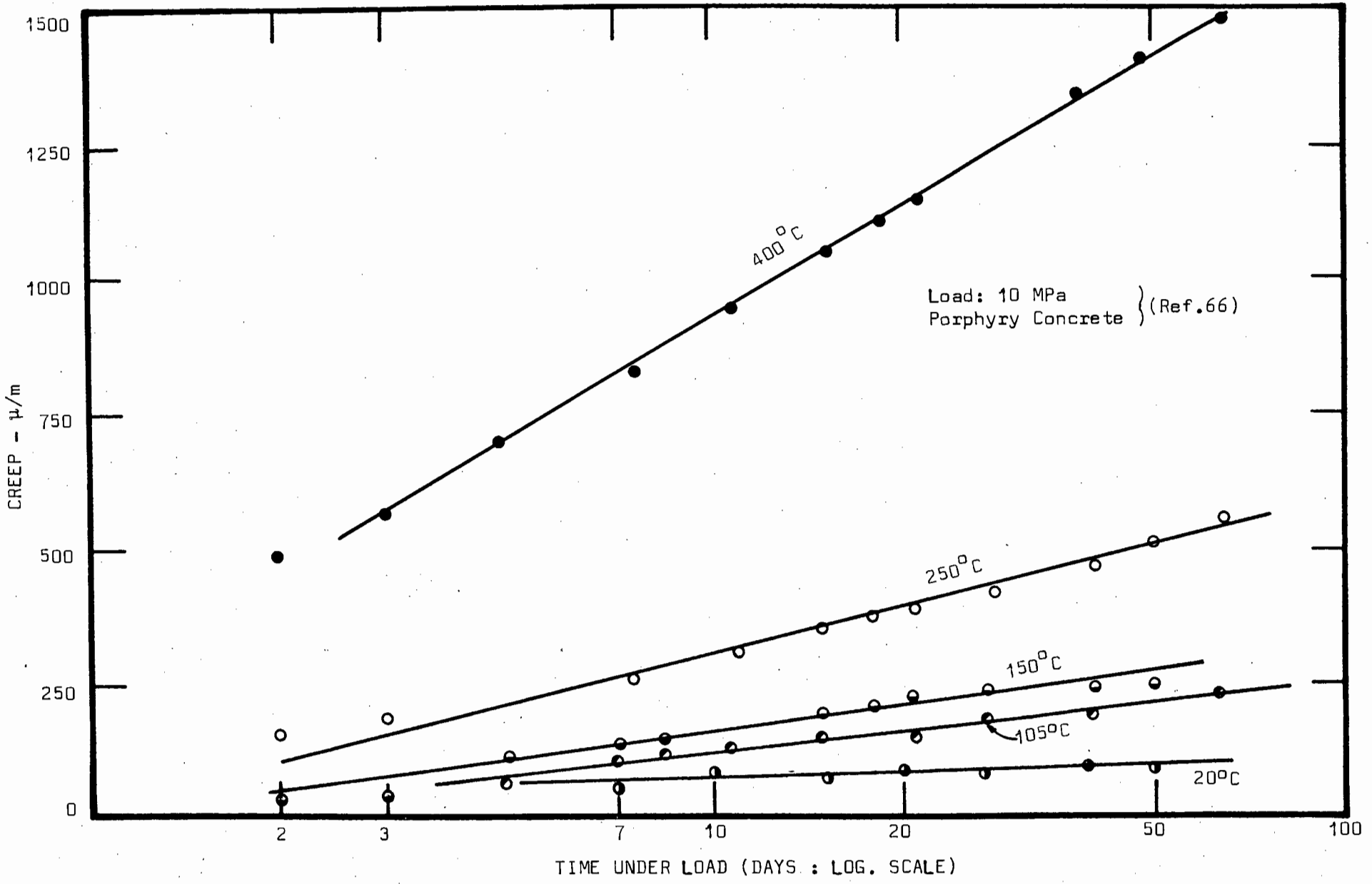
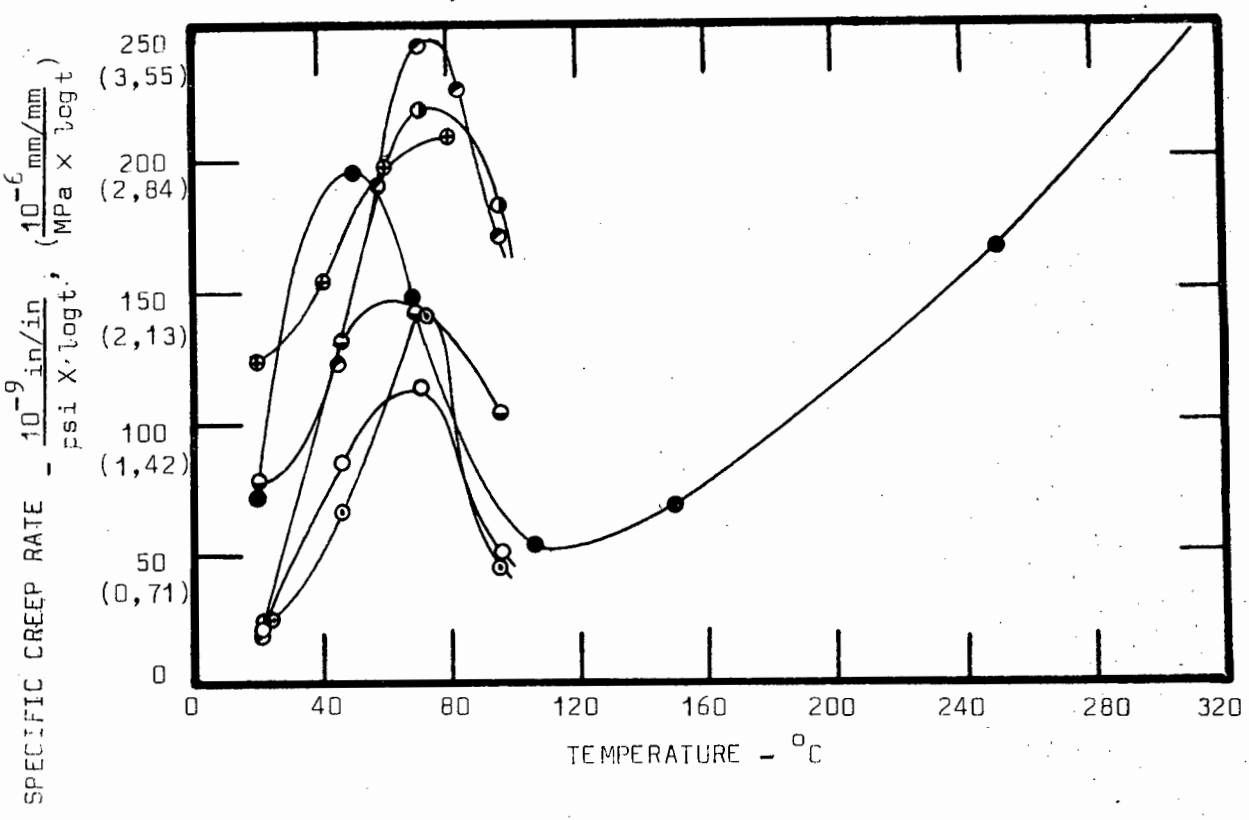


FIG.I.14: The creep of concrete at elevated temperature, after various times under load.

agree to a definite maximum for the creep rate between 50°C and 80°C. In Fig. I.15 the creep rate, as found at various temperatures by different investigators, is plotted against temperature. From these data the definite maximum is apparent. Furthermore, it appears that a minimum creep rate for both sealed and unsealed concrete occurs as the temperature increases to around 100°C. The exception to this trend is the data reported by Marechal[66] for sealed concrete. This investigator[66] found that the creep rate of sealed specimens is greatest at temperatures around 100°C. These results are illustrated in Fig. I.16. In Fig. I.16 it is further apparent that at temperatures above 100°C, the creep rate of unsealed specimens increases most significantly as the temperature increases. Marechal[66] also indicates that the creep rate of pre-dried concrete is less at temperatures below the drying temperature, than the creep rate of concrete which is allowed to dry whilst under load. This behaviour is in accordance with a statement by Neville[30] that "it is not the ambient humidity that is a factor in creep but the process of drying while the concrete is subject to creep".



- Marechal[66]; loaded to 1400 psi after 1 year of moist-curing; 14 days of preheating; loading period 4-60 days; unsealed.
- Nasser and Neville[59]; loaded after 1 year water storage to f/f'_c of 0,45; underwater; loading period 21-91 days.
- Same as above[59] but f/f'_c = 0,25.
- Same as above[59] but stored underwater at test temperature and f/f'_c = 0,45.
- Same as above[59] but f/f'_c = 0,25.
- Nasser and Neville[59]; loaded at 14 days to f/f'_c of 0,35; sealed; underwater; loading period 21-91 days.
- Arthanari and Yu[61]; loaded at 15 days to f/f'_c of 0,20; sealed; loading period 1-60 days.

FIG. I.15: The creep rate of concrete at elevated temperature

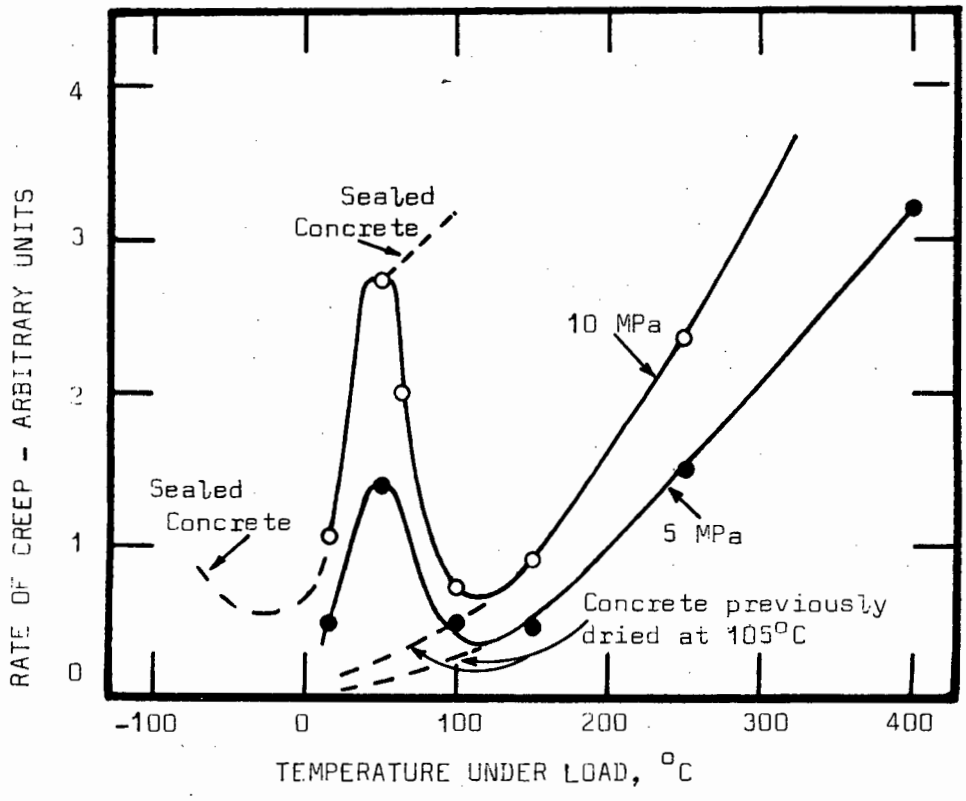


FIG. I.16: The effect of elevated temperature on the rate of creep of concrete.

CHAPTER 2 : THE EFFECT OF SOME EXPERIMENTAL VARIABLES AND EXPERIMENTAL PROCEDURES ON THE STRUCTURAL BEHAVIOUR OF CONCRETE AT ELEVATED TEMPERATURES

2.1 Introduction

When concrete specimens are subjected to heating, the extent of the changes in the structural properties is due to an inter-relationship of certain test parameters and variables. From the literature reviewed it appears that the most important of these are:

(i) Concrete constituents and materials:

- (a) cement type
- (b) aggregate type

(ii) Mix proportions:

- (a) water/cement ratio
- (b) aggregate/cement ratio

(iii) Curing history

(iv) Specimen size

(v) Heating conditions:

- (a) rate of heating
- (b) time at temperature and temperature level
- (c) effects of temperature cycling

(iv) Testing conditions:

- (a) specimens tested hot or after cooling from the test temperature.
- (b) for the case of testing after cooling, the cooling rate and possible autogenous healing effects
- (c) moisture condition of concrete during heating and testing, i.e. whether specimens are allowed to dry or remain fully saturated during heating and testing.

From the literature reviewed, information regarding the specific effect of some of the above variables on the properties of heated concrete can be determined. These studies indicate, however, that the moisture condition of the specimen at testing, as regards whether the water is allowed to evaporate or is contained during heating, is the most important single factor influencing the behaviour of heated concrete. Consequently, reference is always made as to whether the specimens were sealed or unsealed during heating.

2.2 Aggregate Type

Several investigators[1,2,3,5,7,8,17] have studied the specific effect of aggregate type on the behaviour of concrete at elevated temperature. The data of Zoldners[2] is illustrated in Figure I.17; the residual ratio of compressive strength of unsealed concretes containing gravel, limestone, sandstone and expanded slag aggregate respectively, plotted against temperature. Up to 100°C these all show little or no loss in strength. In the 100°C to 200°C temperature range, some gain in strength occurs. At temperatures above 200°C, the respective concretes containing expanded slag and limestone aggregate exhibit a large reduction in compressive strength; the higher the temperature the greater the reduction in compressive strength. This occurs in the gravel concrete at 320°C and in the limestone concrete at 410°C.

Similar trends are not apparent for the flexural strength of the above-mentioned concretes. These results are plotted in Fig. I.18. The flexural strength of all concretes show rapid deterioration with temperature, the higher the temperature the greater the loss in flexural strength. The least strength loss is found in the limestone concrete which retains 40 percent of the unheated flexural strength at 500°C. The same investigator[2] reports that the expanded slag concrete exhibited a residual shrinkage on cooling from all temperatures. The concretes incorporating the other aggregates exhibited a shrinkage when cooled from temperatures below 300°C; when cooled from temperatures above 300°C, residual expansion of these concretes always occurred.

Zoldners[2] concludes that the aggregates exert considerable influence on the property behaviour of concrete at elevated temperatures. Concrete containing limestone aggregate is thought to be more suitable than concrete

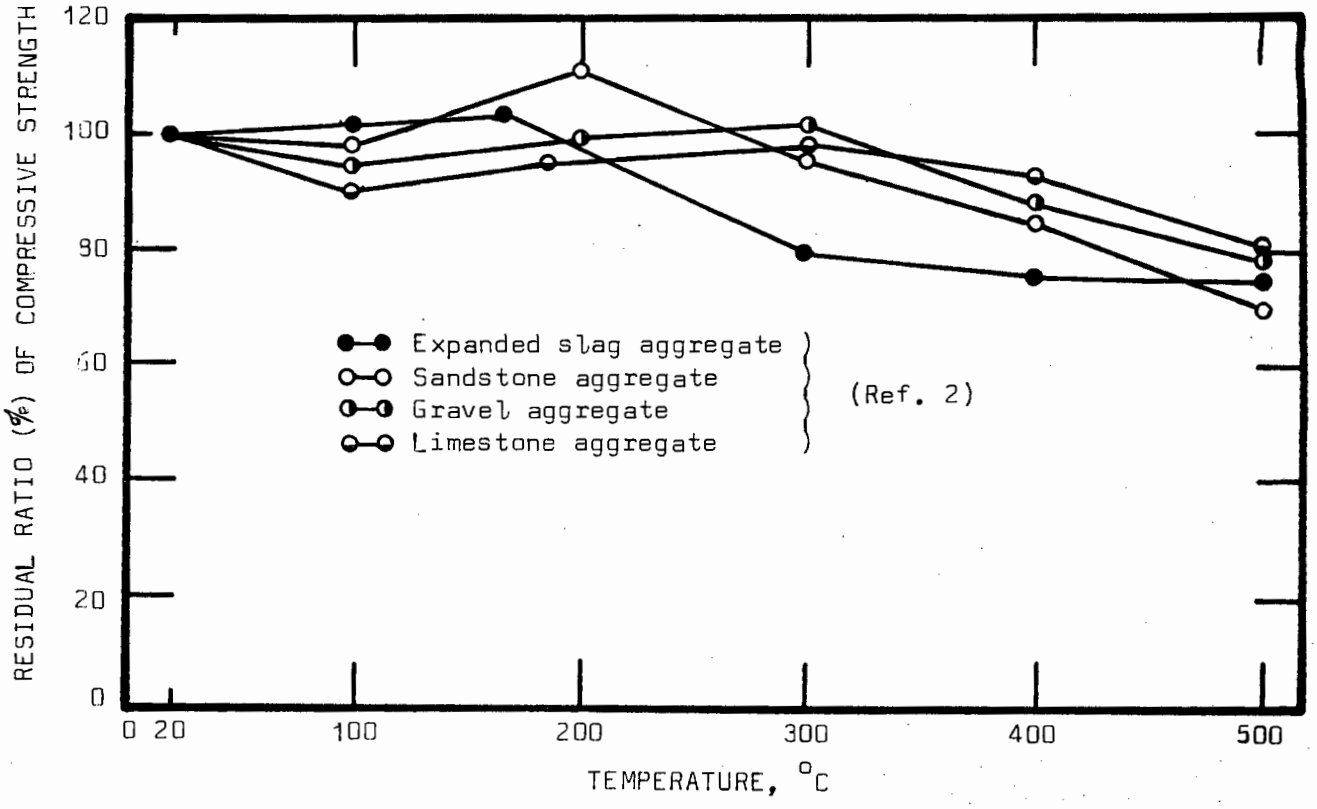


FIG. I.17: The effect of heating on the compressive strength of concretes incorporating different aggregates.

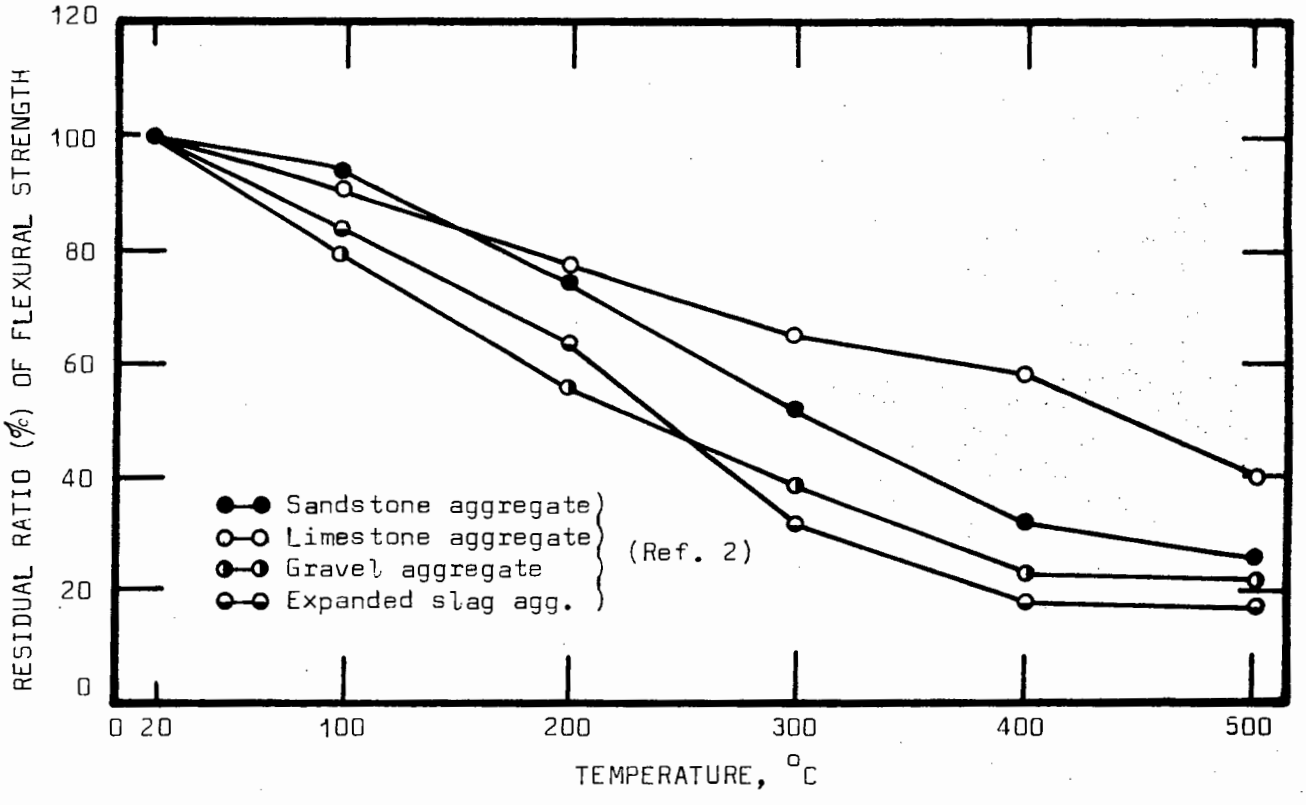


FIG. I.18: The effect of heating on the flexural strength of concretes incorporating different aggregates.

containing igneous gravel or sandstone aggregate. Of all the concretes investigated the expanded slag concrete was found to have the least desirable structural properties at elevated temperature. Worth noting is the fact that this aggregate, by nature of its manufacture, would exhibit relatively low thermal expansion. A possible cause of the poor structural behaviour could thus have been the incompatibility of the thermal expansions of the concrete constituents.

Campbell-Allen and Desai[3] compare the properties of unsealed concretes containing limestone, expanded shale and fireclay brick aggregate respectively. The relative performance of these was assessed from the effects of cycling to 300°C on the compressive strength and flexural strength. This is illustrated in Figs. I.19 and I.20. All concretes show marked deterioration of both compressive strength and flexural strength respectively, as the number of thermal cycles increases. The limestone concrete is the most affected, and the firebrick concrete the least affected, by the heat treatment. In this respect it is worth noting that for the limestone and shale concretes, the authors noted a large number of aggregate particles dislodged from the cement matrix after testing. Relatively few were apparent for the firebrick concrete. With regard to this, Campbell-Allen and Desai[3] point out that the fireclay brick, although having a significantly lower thermal expansion than the cement paste phase, nevertheless had the best performance at elevated temperature of the three concretes investigated. This they attribute to the excellent bonding between the cement and fireclay - a result of the surface texture and shape of the aggregate. The influence of surface texture and shape is further evident from the behaviour of the expanded shale aggregate. This was as stable as the fireclay brick at temperature and had approximately the same thermal expansion coefficient. However, the smooth surface and rounded shape of the expanded shale aggregate caused greater loosening of this aggregate from the cement mortar.

Lankard[1] concludes that up to approximately 260°C the choice of aggregates for concrete heated in the unsealed condition is not too critical, provided the aggregate itself is thermally stable. His findings are based on research of gravel and limestone concretes. For sealed concrete, Lankard[1] considers the choice of aggregate very important. Siliceous aggregates are recommended, since they were found "effectively to diminish the degree of deterioration".

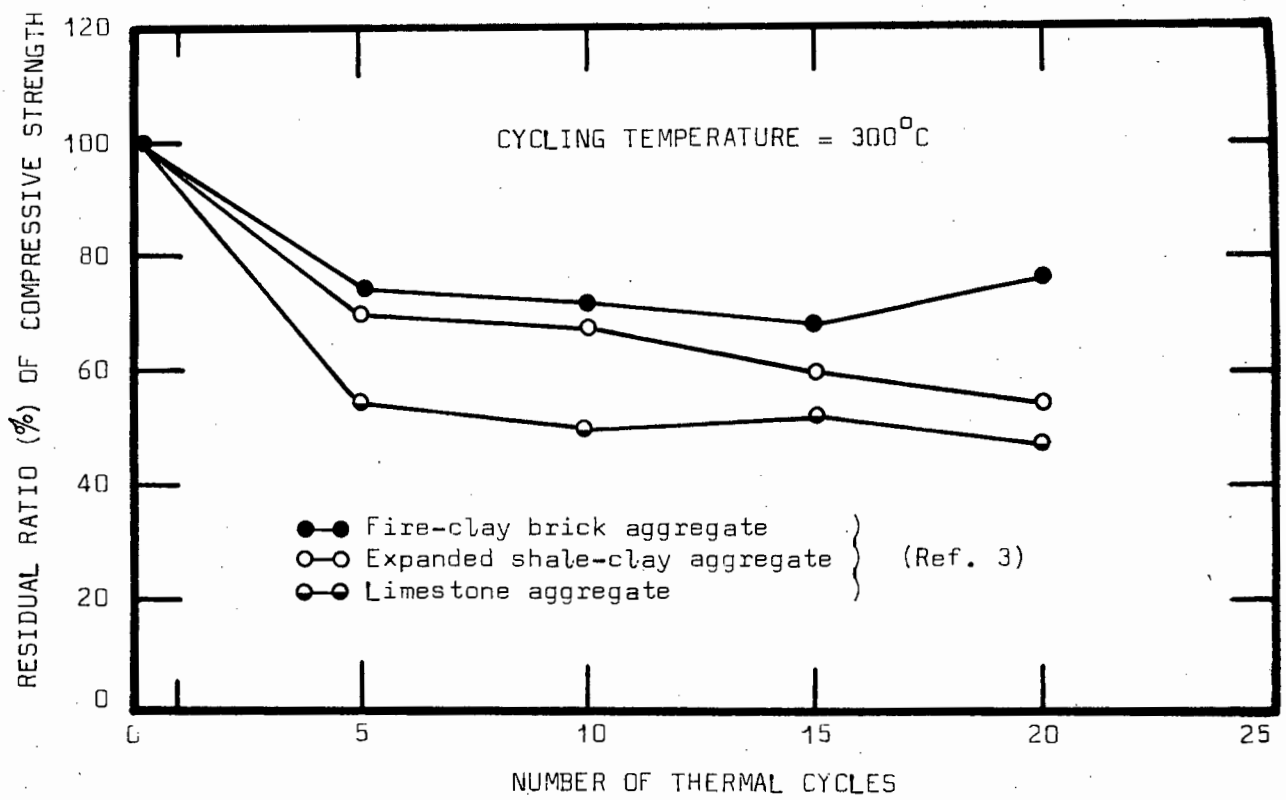


FIG. I.19: The effect of thermal cycling on the compressive strength of concretes incorporating different aggregates.

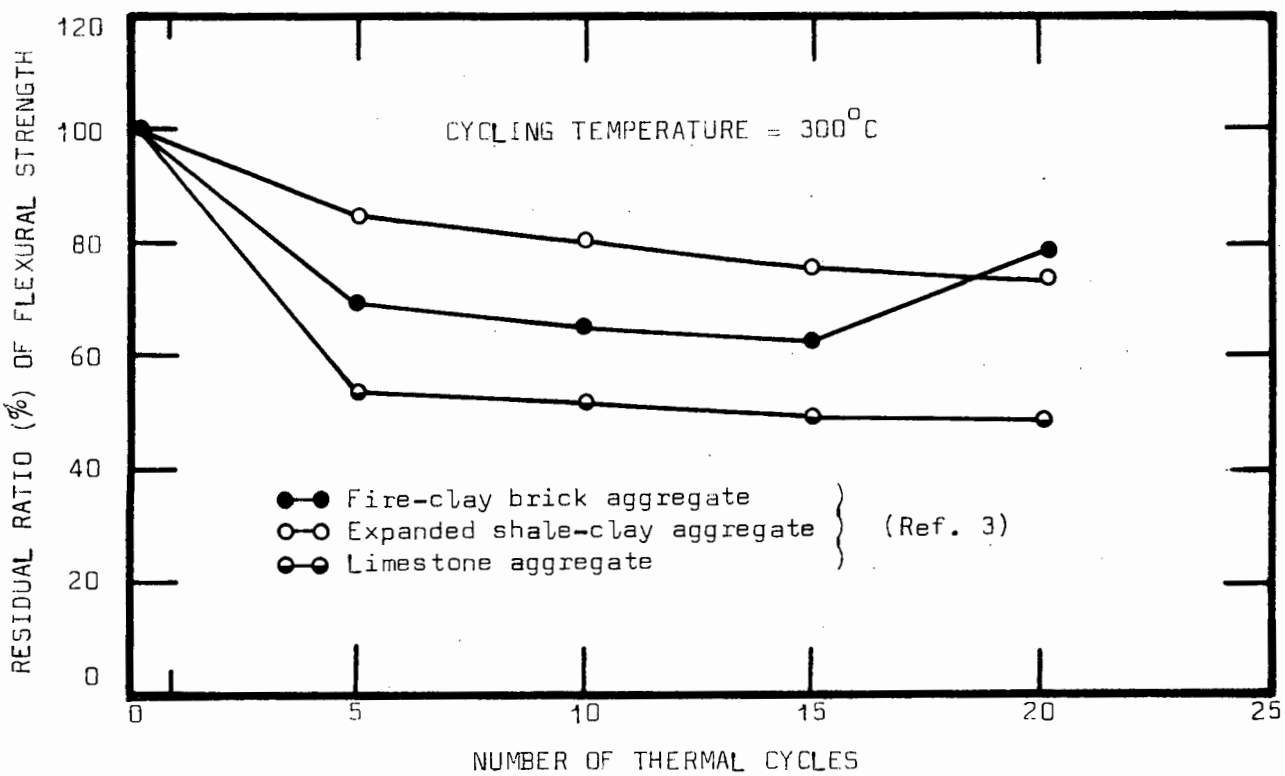


FIG. I.20: The effect of thermal cycling on the flexural strength of concretes incorporating different aggregates.

Harada et al[7] observed the effects of short term heating on the properties of unsealed specimens made with different aggregates. The data for concrete incorporating limestone and sandstone aggregate respectively are illustrated in Fig. I.21. It is apparent that the reductions in compressive strengths are approximately the same for the two concretes studies. The flexural strength and Young's modulus (static) of limestone concrete tend to be more reduced at high temperature than flexural strength and Young's modulus of sandstone concrete. In this respect it is worth noting that the authors[7] found the thermal expansion coefficients of the sandstone aggregate (siliceous) concrete to agree very well with that of the original stone. Limestone aggregate concretes were found to have expansion coefficients much lower than those of the limestone aggregate only.

Crispino[8] proposes that in order to eliminate the reductions in the structural properties of concrete at elevated temperature, the differential movement between the aggregate and cement paste should be as small as possible. The author developed a concrete incorporating barite aggregate (B.H.T. concrete) which he compared with a concrete made with limestone aggregate. The coefficients of thermal expansion of the barite aggregate and neat cement mortar were both between $12{,}5 \times 10^{-6}$/deg C and 14×10^{-6}/deg C, whereas the expansion coefficient of the limestone aggregate was $6{,}5 \times 10^{-6}$/ deg C. After six cycles of temperature to 500°C, the barite concrete exhibited less reduction of compressive strength than the limestone concrete with similar treatment, to a maximum temperature of 350°C. Furthermore, one cycle of heating and cooling resulted in a residual shrinkage of the barite concrete whereas the limestone concrete exhibited residual expansion after similar heating. The author[8] concludes that this illustrates the extent to which microcracking had occurred within the limestone concrete. A factor thought[8] to exert considerable influence in the deterioration was the different thermal expansions occurring along the three crystallographic axes of the limestone aggregate - the Z axis exhibiting markedly less expansion than either the X or Y axis.

The above review indicates that aggregates are of major importance in influencing the behaviour of concrete at elevated temperature. However, the conclusion that the selection of aggregates should be based on the compatibility of the thermal expansion coefficient of the aggregate and cement paste in the range of temperature envisaged, cannot be justified. This is because:

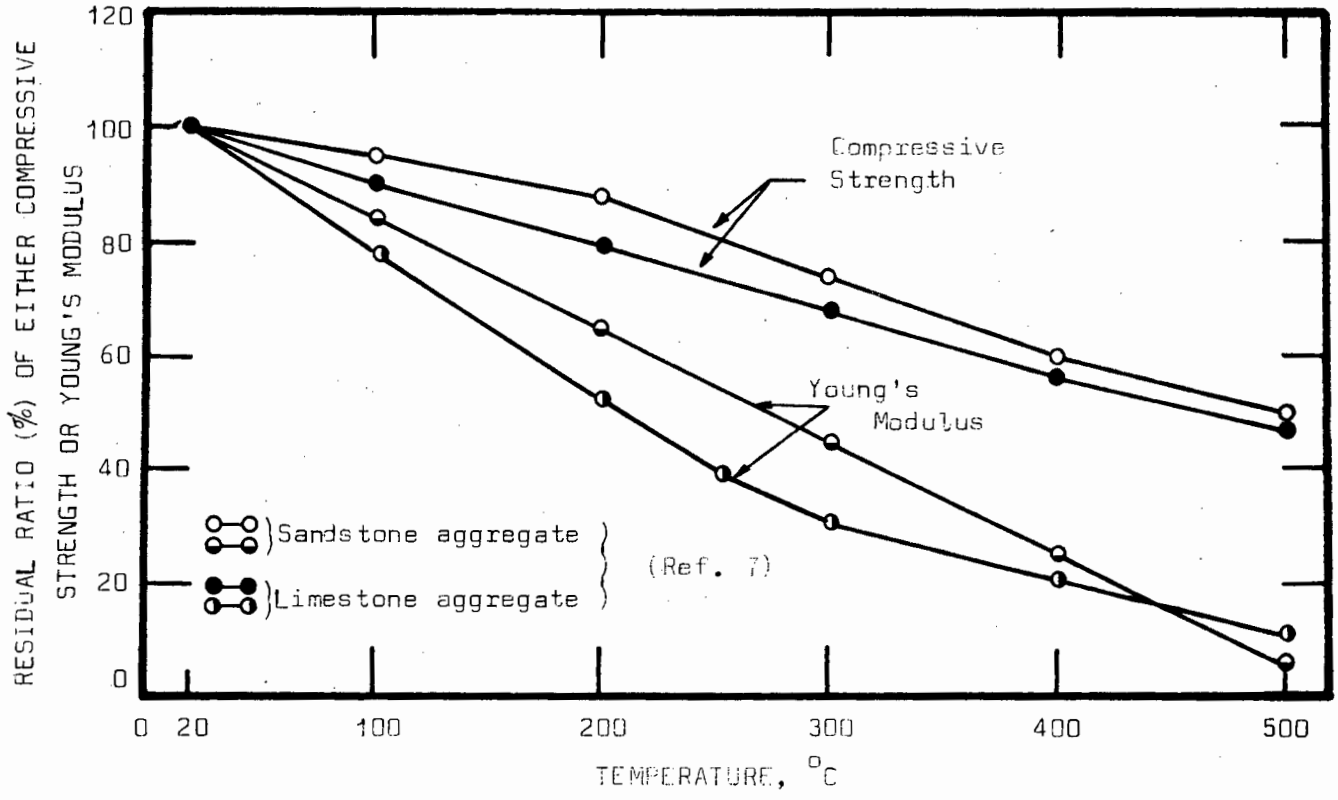


FIG. I.21: The effect of heating on the compressive strength and Young's modulus of concretes incorporating different aggregates.

(i) Factors like the surface texture, shape of aggregate and volumetric concentration of aggregate may also influence the behaviour of concrete made with a particular aggregate type.

(ii) In unsealed concrete the strains which may result from incompatibility of the thermal expansion coefficients of the cement paste and aggregate, are not as large as the strains caused by shrinkage of the paste relative to the aggregate as the paste loses water. For specimens which remain fully saturated during heating, the thermal compatibility of expansion coefficients may be a consideration in the choice of constituents.

Furthermore, it is apparent from the reviewed literature that the emphasis has been primarily on determining the effect of different coarse aggregates on the property behaviour of concrete at high temperature. It should be remembered though, that when two different coarse aggregates are used to make concrete the proportion of fine aggregate is usually not the same in the two cases. The possibility therefore exists that in some instances, when comparing the behaviour of concretes made with different coarse aggregates, the fine aggregate may have influenced the results. The thermal incompatibility of paste and aggregate, and the effects of coarse and fine aggregate on concrete behaviour at elevated temperature, are discussed more fully in Chapter 4 and Chapter 5 of this review.

2.3 Water/Cement Ratio and Aggregate/Cement Ratio

Research by Malhotra[67] indicates that the water/cement ratio (by weight) has little influence on changes of compressive strength in concrete heated to 600°C. The water/cement ratios investigated ranged from 0,37 to 0,64. This observation is in accord with the results of Saeman and Washa[68]: no significant differences in the relative changes of compressive strength at 250°C were observed for concretes having water/cement ratios of 0,48 to 0,84. Below 100°C, however, concretes with a low water/cement ratio exhibit more reduction of heated compressive strength than concretes with a high water/cement ratio.

There is evidence to suggest though, that relative changes occuring in the Young's modulus of heated concrete are more sensitive to changes in the water/cement ratio. Several studies[18,68,69] show that in unsealed concrete at elevated temperature, less proportionate reduction of Young's modulus occurs for specimens of low water/cement ratio than for specimens of high water/cement ratio.

Research data pertaining to the influence of the cement/aggregate ratio on the structural behaviour of heated concrete is limited. Malhotra[67] established that at temperatures up to 220°C lean mixes (low cement/aggregate ratio) exhibit less reduction in compressive strength than rich mixes (high cement/aggregate ratio). These results were obtained on unsealed specimens.

The reviewed literature does not indicate conclusively whether the water/cement ratio, or the cement/aggregate ratio, is the more important parameter regarding the effects of elevated temperature on the structural behaviour of concrete. It is evident though that mix proportions do exert considerable influence on the properties of concrete at elevated temperature. In this regard Davis[18] is of the opinion that concrete made with "low water-cement ratios, and high cement-aggregate ratios will fare better at high temperatures than other mixes".

Furumura[70] investigated the compressive strength of concretes incorporating expanded shale and gravel aggregate respectively. For each aggregate type the water/cement ratios were 0,45 and 0,65; the cement/aggregate ratios 0,47 and 0,26 respectively. The specimens were cured for 4 to 6 months prior to heating in the unsealed condition. The results of these tests are illustrated in Fig. I.22; the residual ratios of compressive strength of the respective mixes plotted against the temperature. From these data it appears that low strength concrete exhibits overall better compressive strength at elevated temperature than concrete of high strength. This is contrary to the conclusion of Davis[18].

2.4 Specimens Tested Hot or after Cooling from Temperature

Considerable difficulty has been encountered in the testing of specimens whilst hot. Consequently, in many instances specimens have been allowed to cool to room temperature before testing. Test data indicate though, that

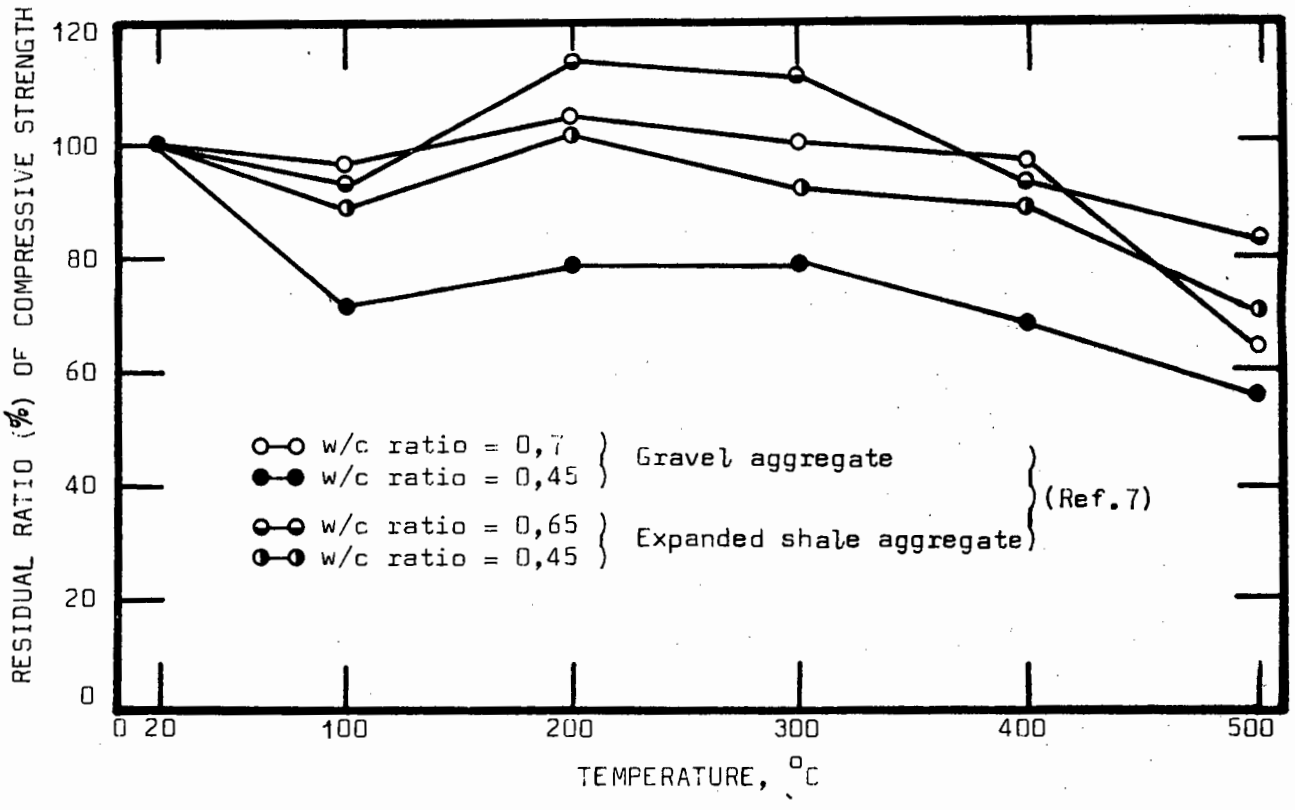


FIG. I.22: The effect of heating on the compressive strength of concretes with different mix proportions.

there can be variation between the results of specimens tested hot and specimens tested after cooling from the test temperature.

The results of Lankard[1] are illustrated in Fig. I.23 and Fig. I.24. These indicate the variation between some structural properties of heated gravel concrete due to testing hot and after cooling. In Fig. I.23 the effect of these conditions on the compressive strength and modulus of elasticity of unsealed concrete is shown. It appears that the general tendency is for specimens to exhibit slightly better behaviour of these properties when tested hot than when cooled before testing. The data for sealed concrete is illustrated in Fig. I.24. Both the compressive strength and Young's modulus of sealed concrete are significantly higher when specimens are cooled to room temperature before testing than when specimens are tested hot.

This was found too by Bertero and Polivka[4]. The authors investigated both the compressive strength and Young's modulus of concrete when tested hot and tested after cooling to room temperature. Both sealed and unsealed specimens were used. The results for sealed specimens indicate that the compressive strength, when tested hot at 150°C is lower than the compressive strength of a specimen cooled from this temperature. The differences were of the order of 5 to 12 percent; the larger of these values for specimens subjected to a greater number of thermal cycles. The modulus of elasticity was found to be affected in a similar way. However, the differences between testing at temperature and after cooling were found to be larger; 9 percent for three thermal cycles to 150°C and 25 percent for fourteen cycles to this temperature. The same investigators also report that the compressive strength and Young's modulus of unsealed specimens tested hot at 150°C are no different to these properties tested after cooling from 150°C.

Weigler[5], however, concludes that for unsealed concrete the strength of hot specimens is generally higher than that obtained after cooling. Data are reported for concrete incorporating quartz and barite aggregate respectively. These concretes were heated to various temperatures ranging from 100°C to 600°C. The author[5] observed that the concrete made with barite aggregate showed smaller property reductions due to cooling than the concrete made with quartz aggregate.

General findings of the literature regarding the influence of cooling before testing can be summarized thus:

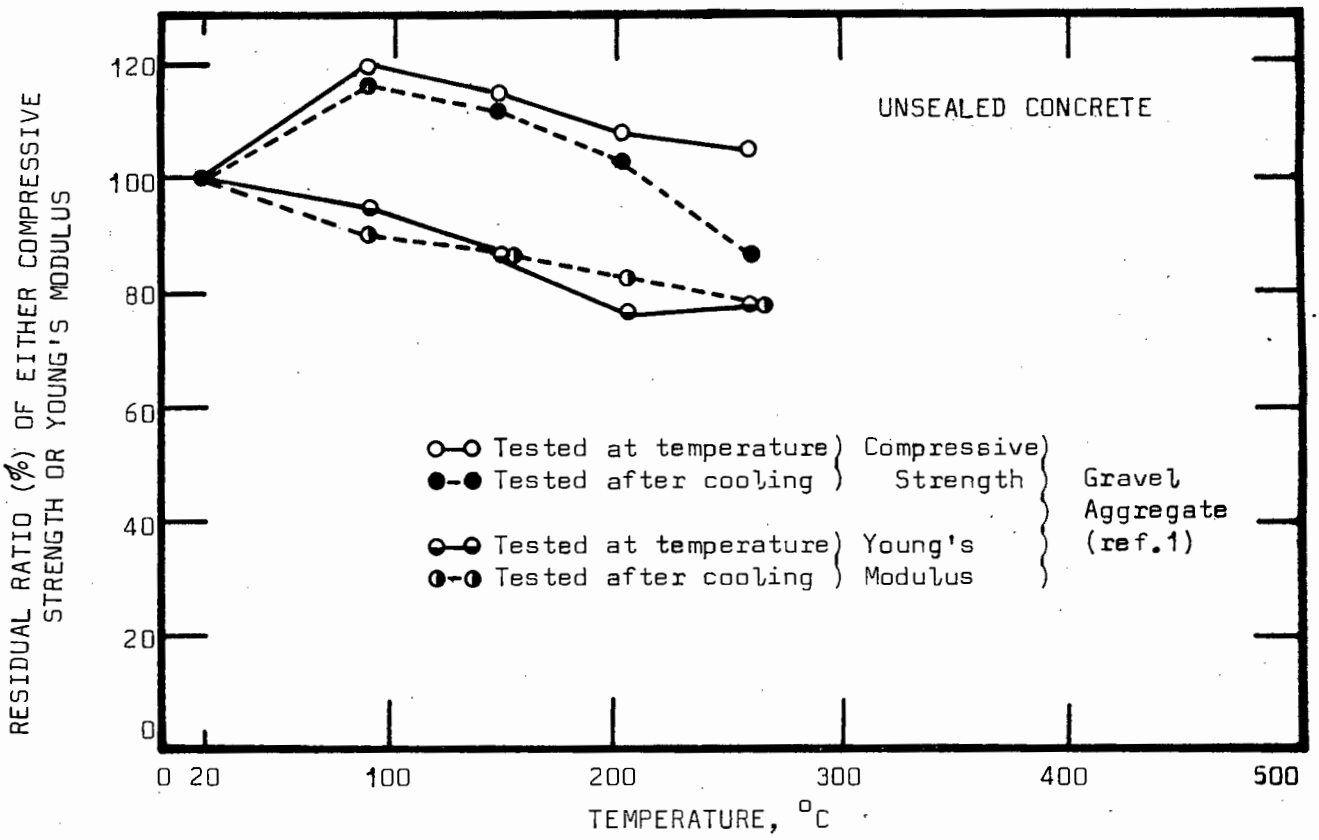


FIG. I.23: The effect of cooling before testing on the compressive strength and Young's modulus of unsealed concrete subjected to heating.

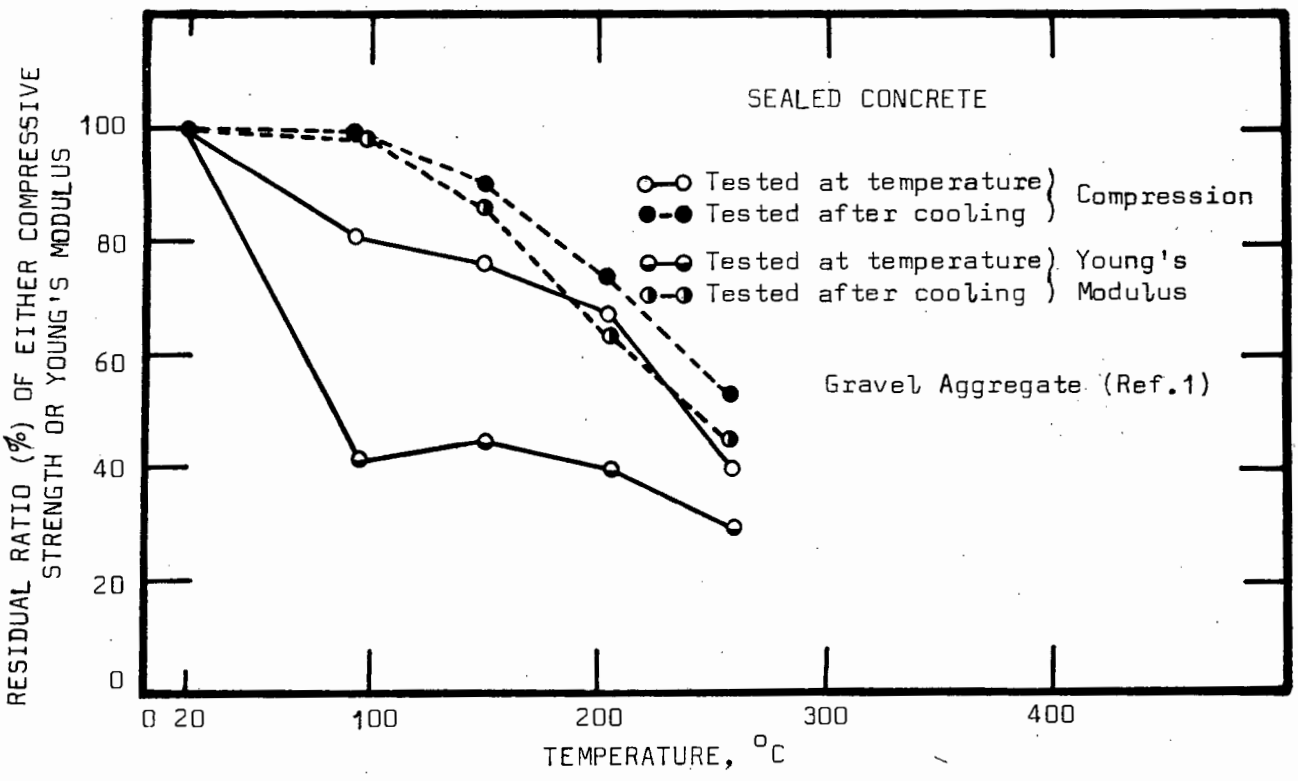


FIG. I.24: The effect of cooling before testing on the compressive strength and Young's modulus of sealed concrete subjected to heating.

(i) Sealed concrete generally exhibits better property behaviour when cooled to room temperature before testing than when tested hot. The difference between the two cases is of the order of 10 percent for compressive strength and approximately 15 percent for Young's modulus.

(ii) Unsealed concrete usually undergoes only minor further reduction in these properties if tested at room temperature after heating.

2.5 Autogenous Healing

If concrete is allowed to cool to room temperature before testing, autogenous healing during the period prior to testing may occur, i.e. some of the structural properties tend to recover to a certain extent the property reduction caused by elevated temperature. This is illustrated in Fig. I.25 and Fig. I.26. The data[7] in Fig. I.25 are for the recovery of compressive strength with time, of cooled concrete specimens previously heated to different temperature levels. The value of the compressive strength at any particular time is expressed as a percentage of the reference value prior to heating. After an initial decrease of compressive strength at two months after cooling, the recovery of compressive strength commences: at 10 months after cooling, compressive strength recoveries of up to 30 percent of the original reference strength had occurred. A similar phenomenon is observed for Young's modulus, illustrated in Fig. I.26. Increases in Young's modulus of 30 to 40 percent after ten months are reported.

The above results are particularly interesting when it is realized that:

(i) The recovery of compressive strength and Young's modulus was for concrete not re-immersed in water; and

(ii) After heating to the indicated temperature, the concrete could not possibly have had any water in the capillary pores of the cement paste. (Data[1] indicate that the gel pores, too, contain no water at these temperatures.)

Consequently, the observed property increases could not have occurred by virtue of a mechanism which requires the presence of water, e.g. an increase in hydration. Two possible causes of the observed behaviour are:

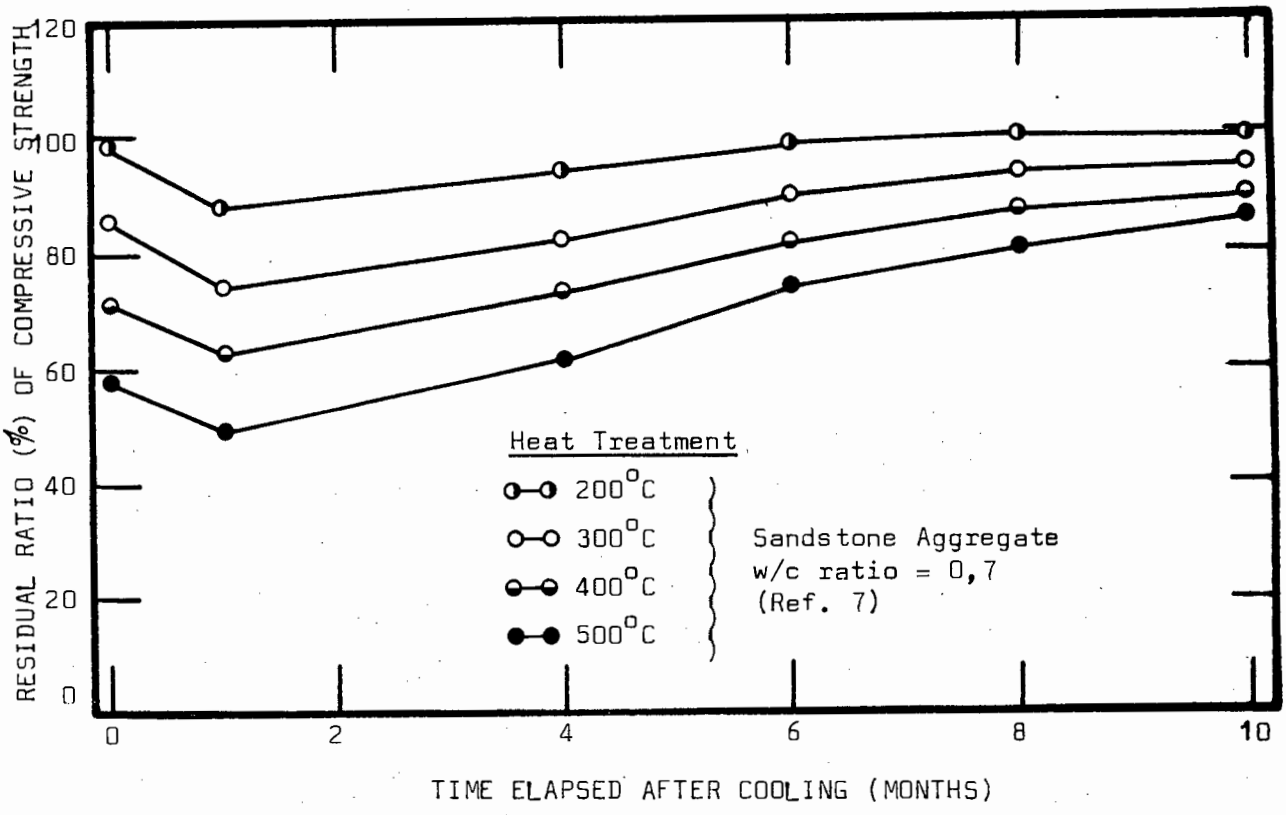


FIG. I.25: The recovery of compressive strength after cooling from heat-treating temperature.

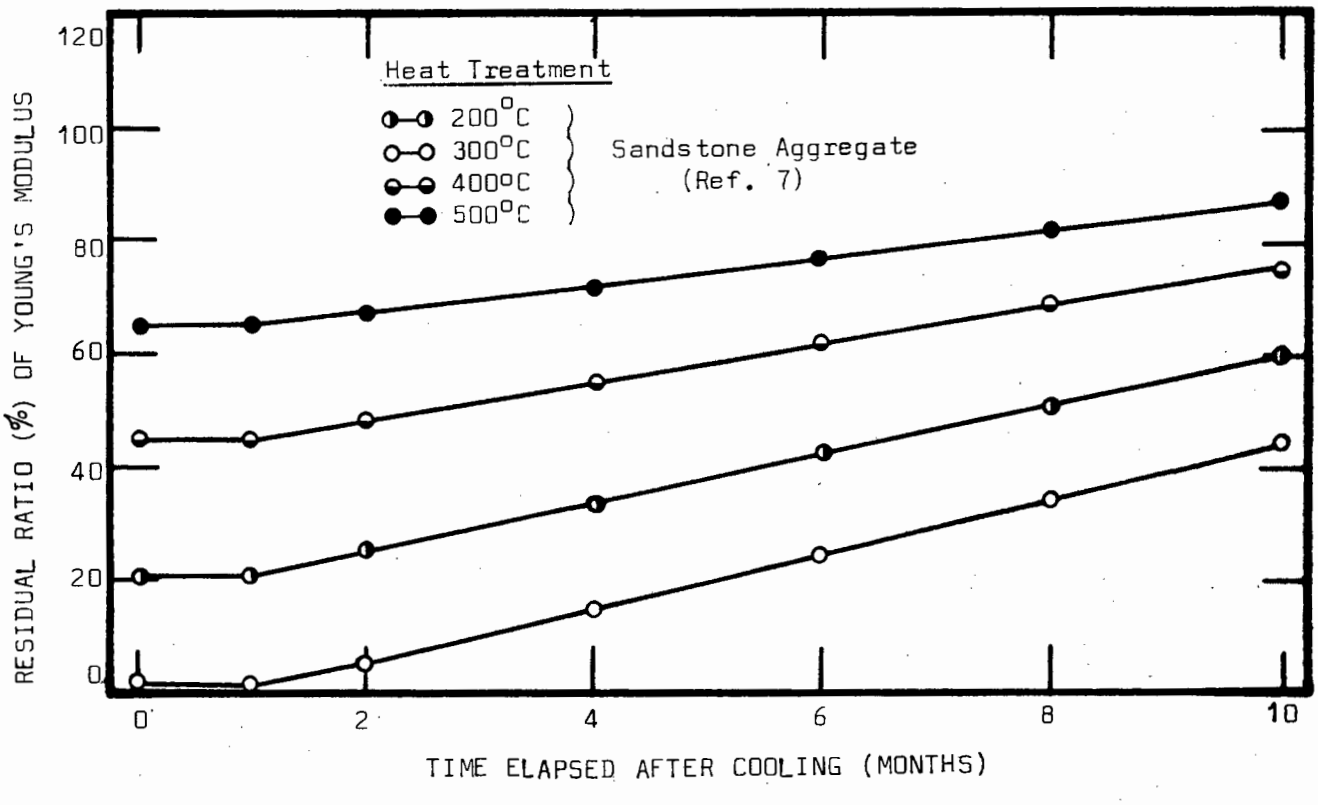


FIG: I.26: The recovery of Young's Modulus in concrete after cooling from elevated temperature.

(i) Carbonation of CaO to $CaCO_3$. It is known that this effect may result in increases in strength[71].

(ii) The effects of creep, i.e. a relaxation of the stresses which occur within the cement paste and at the cement paste/aggregate interface when cement paste shrinks relative to aggregate particles.

These two effects are discussed more fully in Chapter 4 and Chapter 5.

CHAPTER 3 : THE VOLUME CHANGES WHICH OCCUR WHEN CONCRETE IS HEATED TO ELEVATED TEMPERATURE

The dimensional changes which occur in concrete heated to elevated temperature are due to the combined effects of the aggregate and cement paste. In order to ascertain to what extent the dimensional changes of the respective constituents can influence the expansion behaviour of concrete, these changes are discussed before considering the volume changes of concrete.

3.1 Volume Changes of Aggregate at Elevated Temperature

The mineral composition and structure of aggregate is a major factor in determining the coefficient of thermal expansion of concrete. This is because the aggregate usually occupies 60 to 80 percent of the total volume of hardened concrete.

Data indicate that the main factor influencing the thermal expansion of rock, is the proportion of quartz present. Rocks with a high quartz content, such as quartzite and sandstone, have the highest coefficients. These are usually of the order of 12×10^{-6} per deg C. Rocks containing little or no quartz, e.g. limestone, have the lowest coefficients, averaging about 6×10^{-6} per deg C. Igneous rocks (granite, phyolite, basalt, etc.) have medium quartz contents and thus have thermal expansion coefficients between the abovementioned extreme values. In Table I.2, average values of the coefficient of thermal expansion for different rocks are presented[25]. It should be noted though, that these values apply only in the temperature range up to 65^{o}C.

TABLE I.2

The Average Coefficients of Linear Thermal Expansion of Various Rocks (within the temperature ranges to 65°C).

TYPE OF ROCK	Average Coefficient of Thermal Expansion $\times 10^{-6}$/deg C
Quartzite, silica shale, cherts:	11,0 - 12,5
Sandstones:	10,5 - 12,0
Quartz sands and pebbles:	10,0 - 12,5
Clays and mica shales	9,5 - 11,0
Granites and Gneisses:	6,5 - 8,5
Syenites, feldspathic porphyry, Diorites, Andesite, Phonolite, Gabbros, Diabase, Basalt:	5,5 - 8,0
Dense, crystalline, porous limestones:	3,5 - 6,0
Pure calcite:	4,0 - 6,5
Marbles:	4,0 - 7,0
Dolomites, Magnesites:	7,0 - 10,0

Experimental work[26,27] indicates that when different rock types are exposed to elevated temperatures (up to 700°C) the thermal expansion increases several times over that at normal temperatures. The increasing thermal expansion coefficients of a sandstone, limestone, anorthosite and granite, within different ranges of elevated temperature, are shown in Table I.3. Despite the fact that these four rock types fall into three different rock categories, viz. igneous rocks, quartzose rocks and carbonate rocks, they all exhibit the abovementioned trend. Unfortunately, the investigators[26,27] do not indicate to what extent the rocks exhibit permanent expansion or contraction after cooling from the indicated temperatures. This information may be of great value in assessing the suitability of aggregates for use in concrete at elevated temperature; particularly if the concrete is to be subjected to cycles of heating and cooling.

TABLE I.3

The Effect of Elevated Temperatures on the Coefficient of Thermal Expansion of Various Rocks.

Temperature Range	Thermal Expansion Coefficient, $\times 10^{-6}$/deg C			
	Sandstone	Limestone	Anorthosite	Granite
20 to 100°C	10,0	3,0	4,0	4,0
100 to 300°C	15,0	9,0	8,5	13,5
300 to 500°C	21,5	17,0	10,0	26,0
500 to 700°C	25,0	33,0	12,5	47,5

With regard to permanent volume changes which may occur when aggregates are subjected to elevated temperature, the behaviour of quartz-rich rocks is worth mentioning. From the literature reviewed it appears that quartz-rich rocks are stable up to temperatures around 500°C, i.e. on cooling, the original dimensions of these rocks are returned. However, at 573°C an inversion of α quartz to β quartz results in a sudden volume expansion of approximately 2,4 percent[28]. The effect of such an expansion becomes apparent when it is realized that the total thermal expansion due to heating to 570°C is only of the order of 3 percent. At 900°C, dissociation of gases causes a further irregular volume change in quartz-rich rocks[28,31].

The irregular behaviour of certain limestone aggregates when heated has also been reported[3,8,32]. Campbell-Allen and Desai[3] indicate than an endothermic reaction occurs at 280°C in limestone aggregate containing ferrugimous impurities. The authors report that the smallest trace of muscovite and goethite in the limestone add to the instability of this aggregate. Crispino[8] reports the anisotropism of a limestone aggregate; the expansion along the X axis was found to be more than 40 percent greater than that along the Z axis. Harvey[32] shows that within the temperature range of 30°C to 80°C the thermal expansion of a coarse grained limestone is twice as large as that for a fine grained limestone (11,3 and 5,0 $\times 10^{-6}$/ deg C, respectively). The author concludes that finely crystalline rocks are generally more durable from the thermal standpoint than coarse grained ones; the deformations of coarsely crystalline rocks being mostly irreversible after cooling.

3.2 Volume Changes of Cement Paste at Elevated Temperatures

The volume changes exhibited by neat cement paste subjected to heating are closely linked to the water content of the paste. In order to have a better understanding of the prevailing moisture conditions in cement paste, the water content of unheated, hardened paste is first considered.

3.2.1 The Water Content of Hardened Cement Paste

The constituents of unhydrated cement are mainly calcium silicates, calcium aluminates and calcium aluminoferrites, the cement having an average specific surface of approximately 3000 cm^2/g. When mixed with water, these compounds hydrate rapdily at first, and then at a decreasing rate. The main hydration products are calcium-hydroxide crystals and submicroscopic, irregular, needle-like crystals of calcium cilicate hydrate.

The individual particles are not interconnected but separated from each other by small, mostly water filled gel pores. The gel pores have an average diameter of approximately 20^{o}A. Because of their small size, the hydration products are colloidal - the hydrated cement paste thus being considered a gel of the limited swelling class. The cement gel has very large specific surface compared with that of the unhydrated cement - approximately 2×10^6 cm^2/g and 3×10^3 cm^2/g respectively. The approximate porosity of the cement gel is between 26 and 28 percent.

When cement and water are mixed, a system is thus formed which consists of a solid phase of unhydrated cement surrounding comparatively large capillary pores. These capillary pores are filled with water. As hydration progresses, the water from the capillary pores is taken up and gradually replaced by the cement gel. Thus as hydration progresses the volume of capillary pores is simultaneously decreasing. Normally, however, some capillary pores do remain even if the cement is completely hydrated.

The water that has been utilized for hydration of the cement is referred to as the chemically bound water. In addition to the chemically bound water, the cement gel also contains water within the gel pores. Because of the high specific surface of the hydration products (cement gel) and the small diameter of the gel pores, the gel water is strongly adsorbed. It thus has a mobility considerably lower than that of the free water contained in the capillary pores.

Water may thus be present in hydrated cement paste in either of the following three states:

(i) Chemically bound water within the hydration products.*

(ii) Adsorbed water - water physically bound within the gel pores.**

(iii) Free water within the capillary pores, i.e. the capillaries contain all water in excess of that used in (i) and (ii).

In numerous experiments[72], pore structure of cement paste has been quantitatively investigated. No precise distinction could, however, be made between water in the various states; the pore size distribution in the cement paste being continuous, no sharp transition exists between capillary water and gel water. Also, within the hydration products the water is bound in various different ways and with varying degrees of fixation.

Distinction is thus only made between evaporable water and non-evaporable water at a given temperature and pressure. The non-evaporable water is more or less arbitrarily defined as that water which is held in the cement paste after the paste has been dried to constant weight at a temperature of 105°C. This is approximately the same as the water content of the paste at 20°C and zero relative vapour pressure. Though a large portion of this non-evaporable water may be considered as chemically bound, a certain amount of the physically bound water also falls into the non-evaporable category.

The water lost during heating occurs in various stages. This is due to the different degrees of attraction to the cement matrix phase of the types of water present. Furthermore, it does appear that even at the relatively low temperature of 100°C some of the non-evaporable water may be driven off. The loss of water during heating is discussed more fully in subsection 3.2.2.

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* The volume of chemically combined water is usually taken as 23 percent by weight of the hydrated cement.

** The volume of water within the gel pores is calculated from the volume of gel that is formed during hydration and the known porosity of the gel.

3.2.2 The Volume Changes of Cement Paste Subjected to Heating

Investigations[9,10,25] indicate that the volume change of heated cement paste is a complex process, the actual expansion resulting from a combined effect of true thermal expansion and apparent thermal expansion. True thermal expansion is based on kinetic molecular movement of the paste. The apparent thermal expansion arises from swelling pressures. Swelling pressures are caused by a decrease in capillary tension of water held by the cement paste as the temperature increases. No swelling is possible when the paste is dry; consequently it follows that the coefficient of expansion is lower when the paste is dry than when the paste is partly saturated.

When fully saturated paste is heated the coefficient is lower than that for a partly saturated paste. This is because of the diffusion of water from gel pores to capillary pores, the water migration causing some contraction of the paste.

The work of Mitchel[33] and Meyers[10] shows that moisture content may cause the coefficient of expansion of neat paste to vary by as much as 100 percent, with minimum values obtained in both the oven-dry and fully saturated conditions. A maximum value occurs at an intermediate critical moisture content; 65 percent to 70 percent in pastes up to the ages of 6 months, and 45 percent to 50 percent in older pastes. The data of Meyers[10] presented graphically in Fig. I.27 illustrate the above phenomena.

From the abovementioned studies it appears that the thermal expansion of a saturated paste is usually in the range 9×10^{-6}/deg C to 10×10^{-6}/deg C. However, in a paste which is losing water (as opposed to a paste tested at a particular moisture content) the paste will have a continually changing thermal expansion coefficient. This condition arises when paste is heated to high temperature. Furthermore, in a paste that is losing water, considerable shrinkage may occur. The extent of this shrinkage is directly related to the type of evaporable water that is lost. Ishai[34] concludes that at least four mechanisms contribute to drying shrinkage of concrete. These involve five different types of evaporable water, each type differing in its degree of attraction to the solid phase. These are:

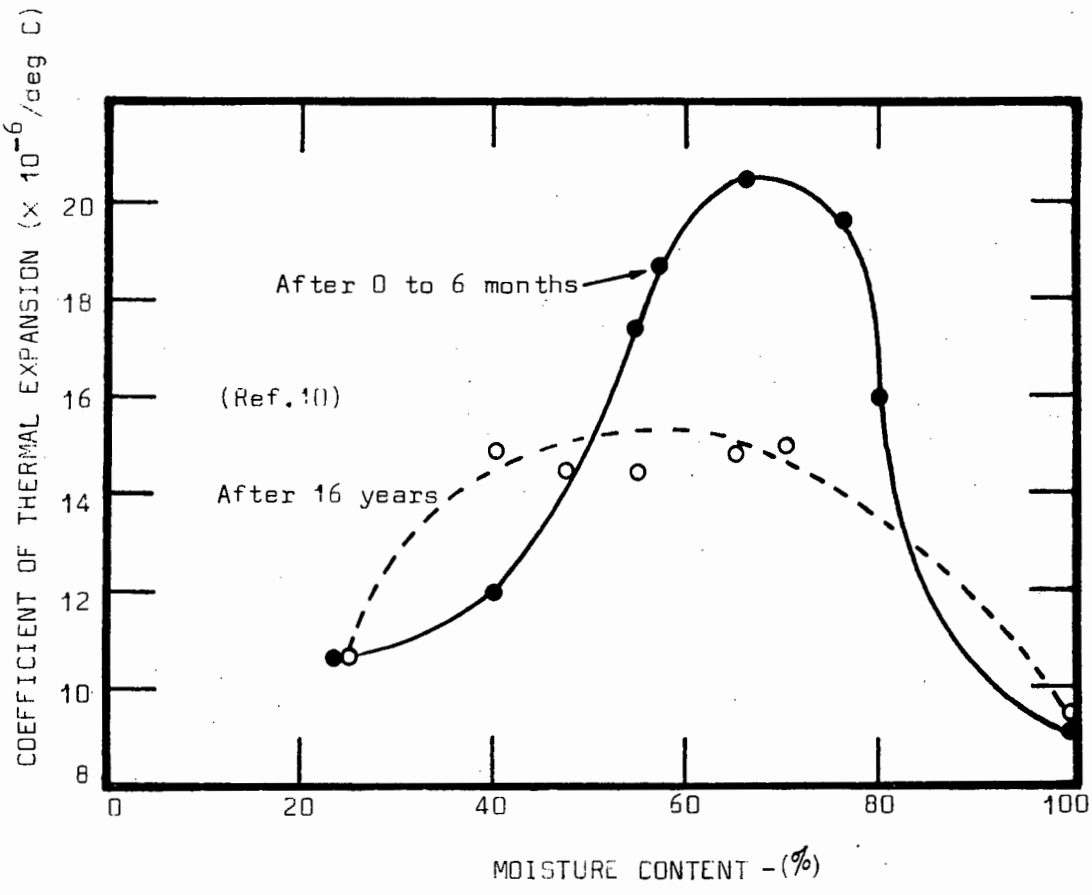

FIG. I.27: The effect of moisture content on the thermal expansion coefficient of hardened cement paste.

(i) water in capillary pores

(ii) water in gel pores

(iii) water adsorbed on crystal surfaces

(iv) adsorbed water confined between adjacent crystal surfaces

(v) zeolitic or intracrystalline water

When paste is heated, the free water is removed in approximately the order listed above. A complete desorption/re-adsorption cycle results in a hysteresis of the shrinkage strain versus moisture loss curve. This indicates that a certain portion of the drying shrinkage is irrecoverable. The permanent shrinkage is associated[1,34] with types (iv) and (v) evaporable water and is thus only significant as complete dryness is approached.

Of particular importance to the present discussion is the fact that total removal of evaporable water is reported to result in a shrinkage of 2 percent in cement paste[31]. Furthermore, the removal of chemically combined water from the hydrated cement phase also results in a shrinkage of the cement paste. Kalousek[35] and Brunauer[36] established that the removal of such from tobermorite gel results in considerable contraction of the paste. This is primarily apparent in the c dimension of the unit cell (basal, interlayer) which has been found to undergo shrinkage of up to 32 percent. Although the a and b dimensions also undergo slight modification, this is considered insignificant when compared with that of the c dimension. Brunauer[36] concludes that the shrinkage accompanying the removal of the bonded OH water and interlayer water from the hydrate may produce cracking.

In addition to shrinkage caused by the loss of evaporable and non-evaporable water when concrete is heated, the effect of carbonation shrinkage[1] should be considered. Carbonation shrinkage is quite distinct from drying shrinkage However, it is also dependent on the moisture content of the paste and the relative humidity of the ambient medium[51]. Carbonation shrinkage occurs when CO_2 present in the atmosphere reacts, in the presence of moisture (the agent really being carbonic acid) with calcium and oxygen ions (from $Ca(OH)_2$) to form $CaCO_3$. In this regard, Neville[51] indicates that carbonation shrinkage probably results from "The dissolving of crystals of $Ca(OH)_2$ while under a compressive stress imposed by the drying shrinkage". The author[51] proposes that the $CaCO_3$ which is precipitated is deposited in spaces free from stress; the compressibility of the cement paste thus being temporarily increased. This increase in compressibility of the paste manifests itself as an increase in shrinkage of the paste.

Carbonation increases the shrinkage only at intermediate moisture conditions of the paste. When the paste is too dry there is insufficient water in the pores within the cement paste for CO_2 to form carbonic acid. On the other hand, when the pores are full of water the diffusion of CO_2 into the paste is very slow. Furthermore, as Neville[51] points out, when the paste is saturated "it is also possible that the diffusion of calcium ions from the paste leads to a precipitation of $CaCO_3$, with a consequent clogging of surface pores".

It may be inferred from the above discussion that when concrete is heated and complete loss of water from the gel pores and capillary pores occurs, there would be no tendency towards carbonation. Also, the effect of carbonation on heated concrete at (i) intermediate moisture content and (ii) in the fully saturated condition, would be negligible. This is because the solubility of calcium hydroxide in water decreases as the temperature increases. Values obtained by Bassett[52] for the solubility of CaO as a function of temperature are given in Table I.4.

TABLE I.4

The Solubility of CaO as a Function of Temperature.

Temperature ^{o}C	0	10	18	25	50	75	100
CaO - g/litre	1,30	1,25	1,20	1,13	0,92	0,72	0,52

From the above table it is apparent that there would be a tendency toward precipitation, rather than dissolution of $Ca(OH)_2$.

In an investigation by Lea and Stradling[37] the length changes of hardened Portland cement paste at elevated temperature were determined. The results of the investigation are illustrated in Fig. I.28: the percentage change in length of cement paste specimen plotted against temperature. Up to a temperature of $100^{o}C$ the cement paste expands. As water is given off, and if the temperature is sustained sufficiently long, a contraction of the paste occurs. This contraction more than equals the previous expansion, i.e. the paste specimen is now shorter than the original length prior to heating. As the temperature increases, the contraction of the paste continues. This is probably due to either:

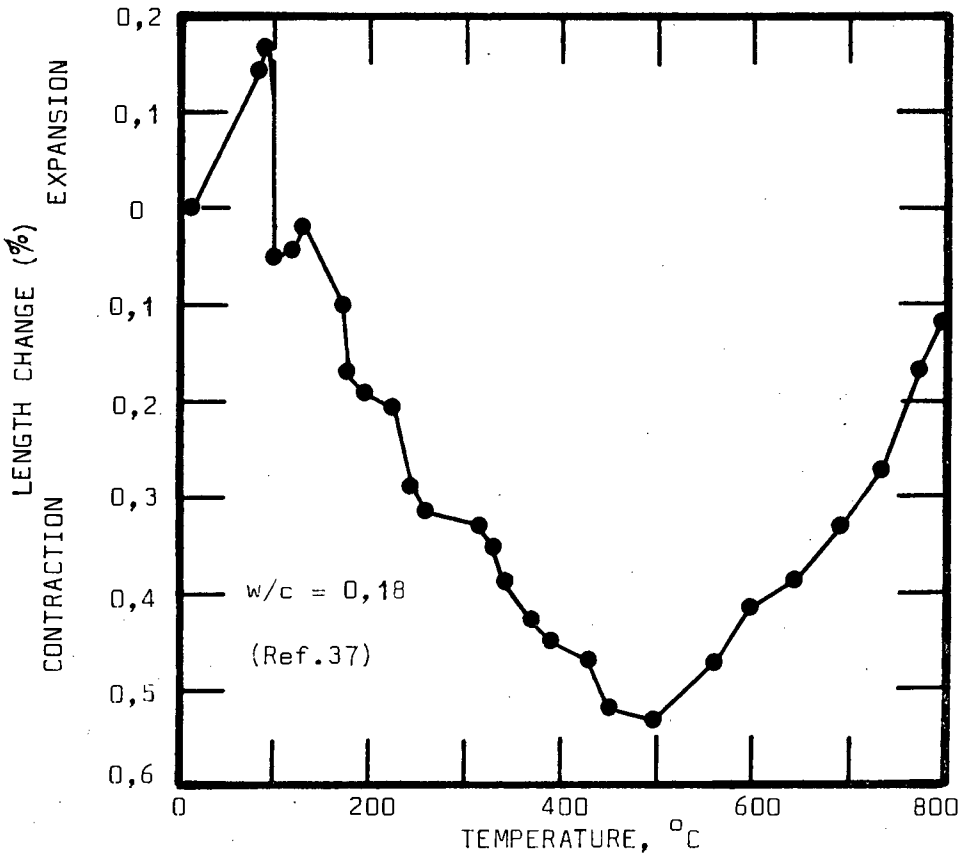

FIG.I.28: Length change of hardened cement paste at elevated temperature.

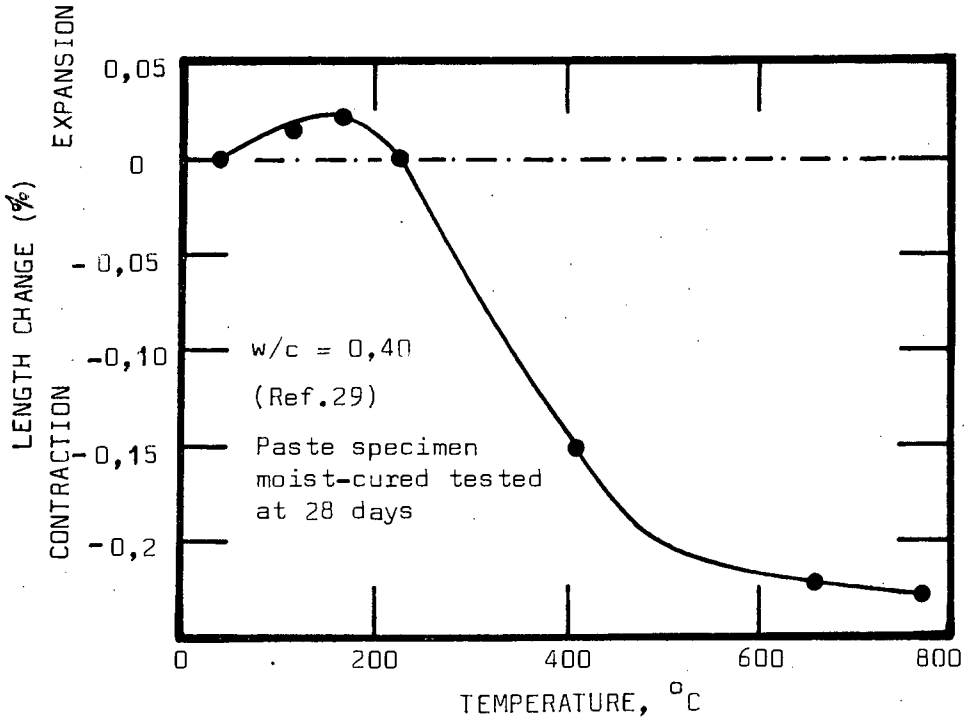

FIG.I.29: The length change of a 0,40 w/c ratio hardened cement paste at elevated temperatures.

(i) the most firmly held evaporable water being driven off, and/or

(ii) the loss of chemically bound water.

It is apparent from Fig. I.28 that the contraction which accompanies the heating of cement paste may be as large as 0,5 percent at 500°C. Furthermore, this result was obtained on a specimen having a w/c ratio of 0,18; if paste specimens with higher w/c ratios are tested, they may exhibit even larger contractions.

The results of Philleo[29] obtained from linear deformation measurements on a 0,40 w/c ratio paste are illustrated in Fig. I.29. These data indicate that contractions of 0,5 percent and 2,0 percent may occur at temperatures of 250°C and 500°C respectively. This is substantiated by the work of Lankard[38] shown in Fig. I.30. The paste specimens had a w/c ratio of 0,60 and exhibited a contraction of 0,9 percent after approximately 40 hours heating at 250°C. It was found by the same investigator[38] that if the capillary water is removed from the paste prior to heating, the final contractive deformation of the paste after 40 hours at 250°C may be as large as 1,7 percent. This is illustrated in Fig. I.31. Lankard[38] also shows that if paste specimens are heated sufficiently slowly, they may never exhibit expansion, i.e. the contraction due to the loss of water is always greater than the expansive effects due to increased thermal energy.

Figs. I.30 and I.31 also indicate that the contraction exhibited by the paste specimen is not a function of temperature alone, i.e. once the maximum temperature is attained, the time of exposure at this temperature has a large influence on the ultimate contraction. This was shown too by Harada[7] and Dettling[25]. In Fig. I.32 the contraction of cement paste at various temperatures is plotted[25] against time. It is apparent that at all the test temperatures the contractive deformation increases as the heating time increases.

3.3 The Thermal Expansion of Concrete at Elevated Temperature

The thermal expansion of fully saturated concrete heated to temperatures higher than 60°C has not been extensively investigated. The results of Roux[20], obtained from expansion measurements on a fully saturated quartzite

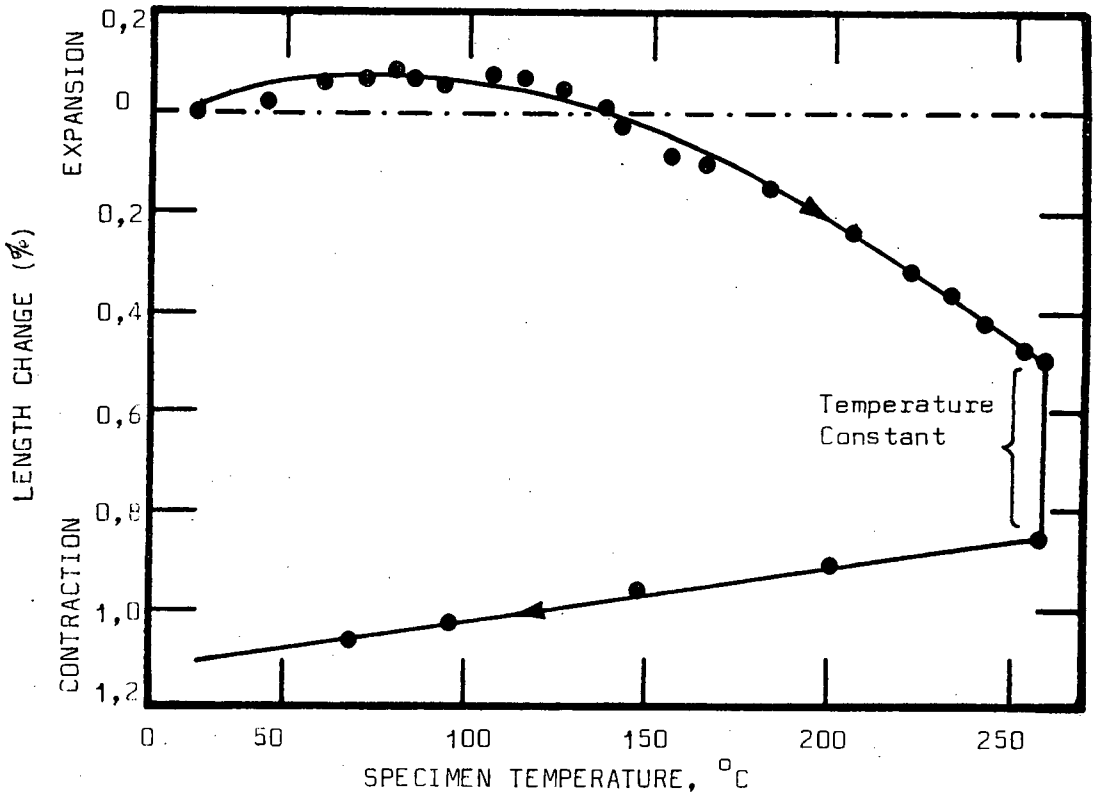

FIG. I.30: The effect of heating on the length change of a 0,60 w/c paste

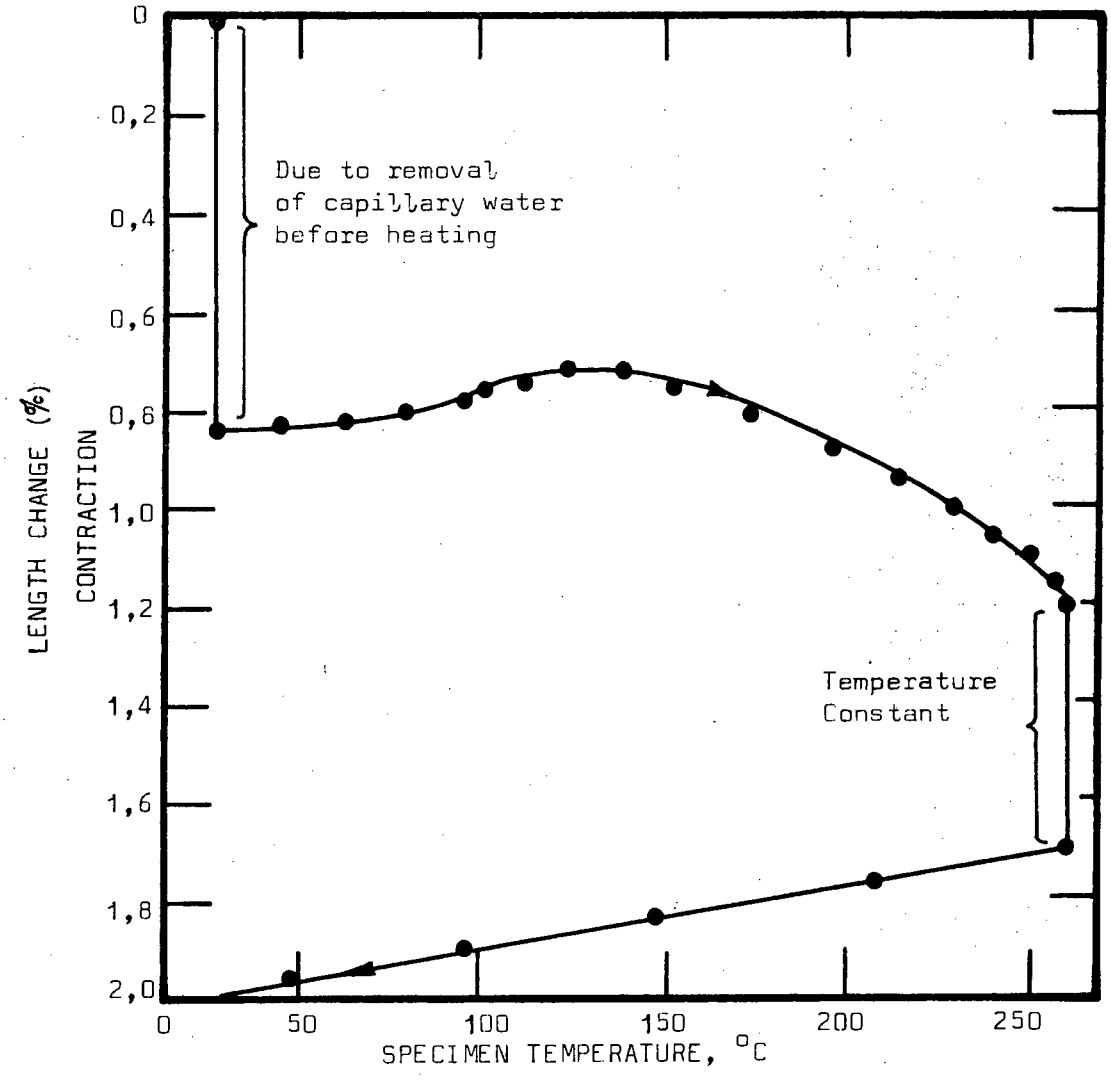

FIG. I.31: The effect of heating on the length change of a 0,60 w/c paste containing no capillary water.

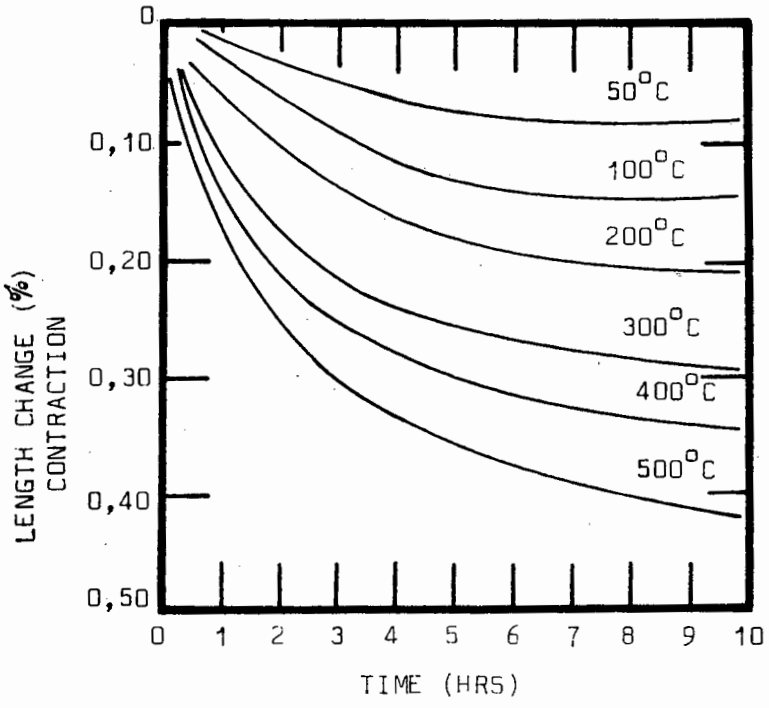

FIG. I.32: The shrinkage of hardened cement paste at sustained elevated temperatures

aggregate concrete, indicate that at 100°C the coefficient is approximately 15 percent smaller than the value found for unsealed specimens at this temperature. Of particular interest are the residual expansions exhibited by the saturated concrete specimens after cooling to the pre-heating temperature. In some instances the residual expansions were as large as $1{,}04 \times 10^{-4}$ mm/mm. This is substantiated by the work of Hannant[21] and that of Bertero and Polivka[4]. Hannant[21] reports that residual expansions of up to 4×10^{-4} mm/mm occurred for concrete specimens cooled to room temperature after prolonged heating at 90°C.

When unsealed concrete is heated to elevated temperatures the absolute expansion due to the increased thermal energy is reduced by shrinkage accompanying the loss of evaporable, and in some instances non-evaporable, water, i.e. a property measurement is being made under conditions where the property itself may be continually changing[1]. The observed absolute expansion or linear deformation is thus due to three effects, viz.

(i) Expansion due to the increased thermal energy.

(ii) Swelling pressures arising from the increase in capillary tension as the paste loses water.

(iii) Shrinkage accompanying the loss of water from the cement paste.

Research by Marechal[14] illustrated in Fig. I.33 shows the linear deformation of unsealed quartzite concrete during heating. In this diagram, strain ($\Delta l/l$) is plotted against temperature. Referring to the characters shown in Fig. I.33:

A - B represented the combined effects of expansion of the hardened cement phase and aggregate. This portion of the curve is not dissimilar to that which would be obtained for sealed specimens in this temperature range.

B - C shows that the shrinkage accompanying loss of evaporable water is retarding the linear deformation of the specimens caused by thermal expansion effects.

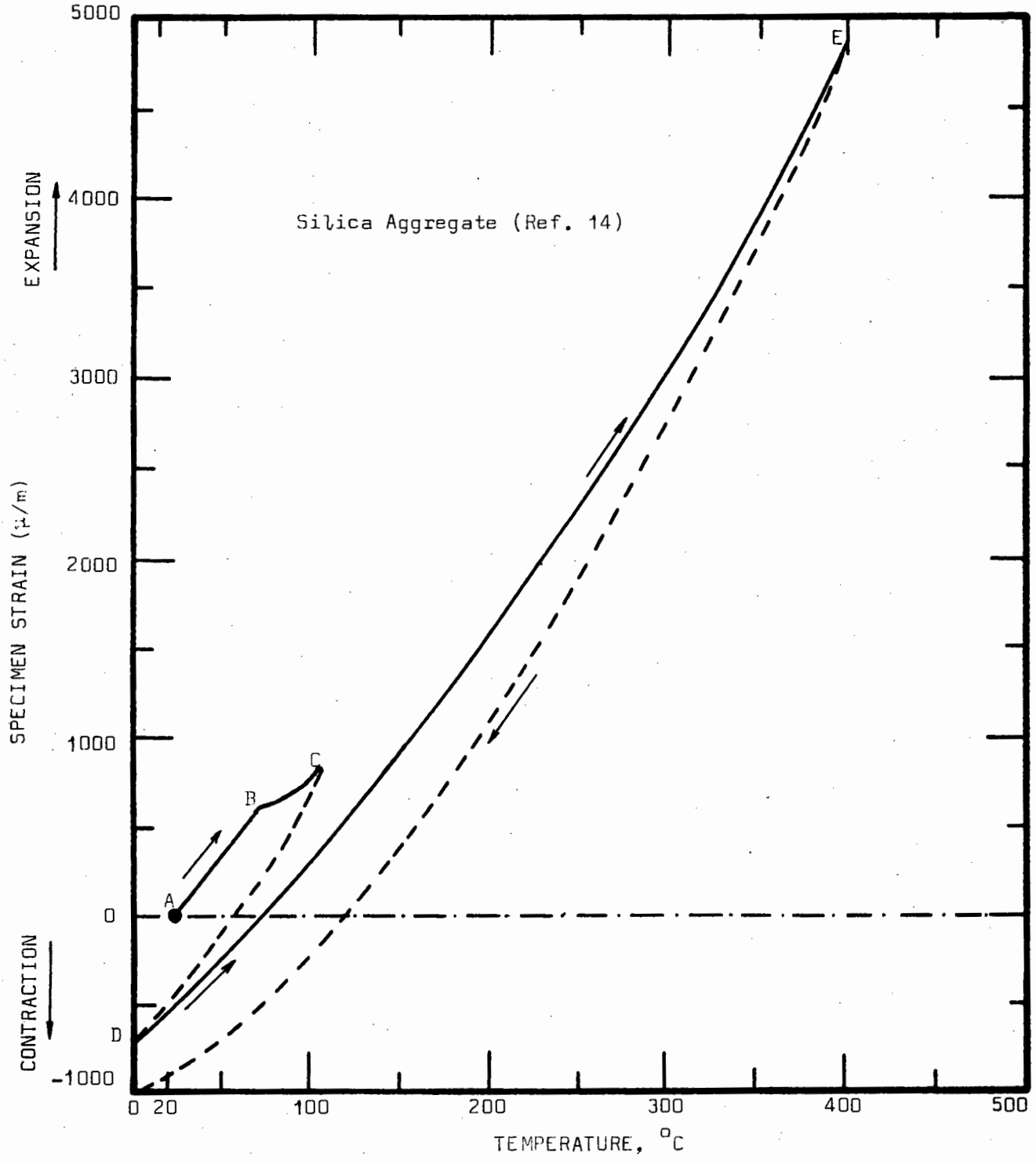

FIG. I.33: The effect of heating on the linear deformation of unsealed concrete.

C - D illustrates that the loss of evaporable water manifests itself as an overall shrinkage when the specimen is cooled to room temperature.

D - E represents the linear expansion for unsealed concrete.

Values of the coefficient of thermal expansion (calculated from the linear expansion) range from 7,0 × 10^{-6}/deg C at 100°C, to 12 × 10^{-6}/deg C at 400°C. It appears therefore, that the coefficient of thermal expansion increases as the temperature increases.

Harada et al[7] determined the coefficient of thermal expansion of an unsealed limestone concrete. The reported values of the coefficient range from 7,5 × 10^{-6}/deg C at 200°C to 12 × 10^{-6}/deg C at 500°C. These investigators indicate that the observed values of thermal expansion were slightly smaller than the thermal expansion exhibited by only the aggregate at these temperatures. Concrete made with a siliceous aggregate, however, had coefficients of thermal expansion which agreed very well with those of the original aggregate. Values of 6 × 10^{-6}/deg C to 10,5 × 10^{-6}/deg C for concrete incorporating siliceous aggregate are reported in the temperature range from 200°C to 500°C.

Table I.5 illustrates the difference between the coefficient of thermal expansion of the standard concrete (limestone aggregate) and B.H.T. concrete (barite aggregate) developed by Crispino[8]. Measurements were made on unsealed specimens, the heating procedure having allowed for total removal of evaporable water.

TABLE I.5

A Comparison of the Thermal Expansion Coefficients of the Limestone Concrete and the B.H.T. Concrete Developed by Crispino[8].

Temperature Range (°C)	Thermal Expansion Coefficient, × 10^{-6}/deg C	
	Standard Concrete	B.H.T. Concrete
50 - 150	8,0	13,40
150 - 250	8,4	13,50
250 - 350	11,4	13,50

Of particular interest are residual strains recorded after cooling from 360°C. The limestone concrete exhibited residual expansion of 2,96 mm/m as compared to a residual contraction of 0,40 mm/m exhibited by the B.H.T. concrete. Crispino[8] concludes that this illustrates the extent to which microcracking between the mortar and aggregate occurred within limestone concrete. He attributes the microcracking to:

(i) incompatibility between the expansion of limestone aggregate and mortar; and

(ii) the anistropy of the limestone aggregate.

Both of these effects are illustrated in Fig. I.34: the respective expansions of limestone based mortar and limestone (in three orthogonal directions) plotted against temperature. Crispino[8] points out that in the case of the B.H.T. concrete, the barite coarse aggregate had a thermal expansion which agreed very well with that of the baritic mortar. This is also illustrated in Fig. I.34.

The linear expansion data obtained by Philleo[29] are given in Fig. I.35. The concrete mix was made with calcareaus aggregate and the expansion determined on unsealed specimens. It is apparent from Fig. I.35 that at approximately 300°C the slope of the linear expansion curve increases, i.e. the thermal expansion appears to increase. This behaviour was found also for an expanded shale concrete[29] and agrees with the findings of Harada[7], Marechal[14] and Crispino[8] that the coefficient of thermal expansion tends to increase as the temperature increases. However, Philleo[29] indicates that in the region in which the thermal expansion coefficient appears to increase, the concrete specimens cool with a lower coefficient, i.e. permanent dilation of the concrete occurred during heating.

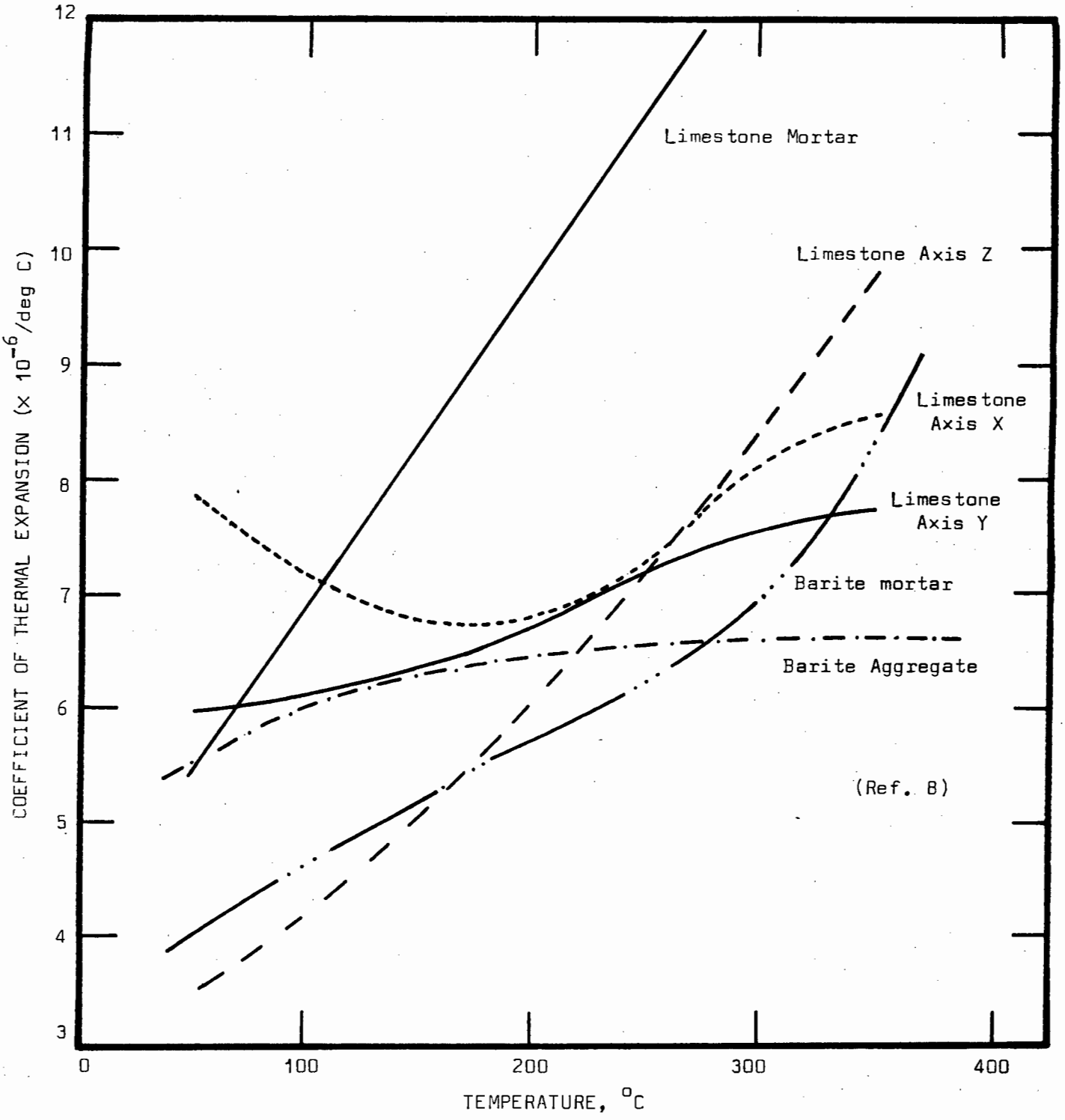

FIG.I.34: The coefficient of thermal expansion of limestone, limestone mortar, barite aggregate and barite mortar at various temperature levels.

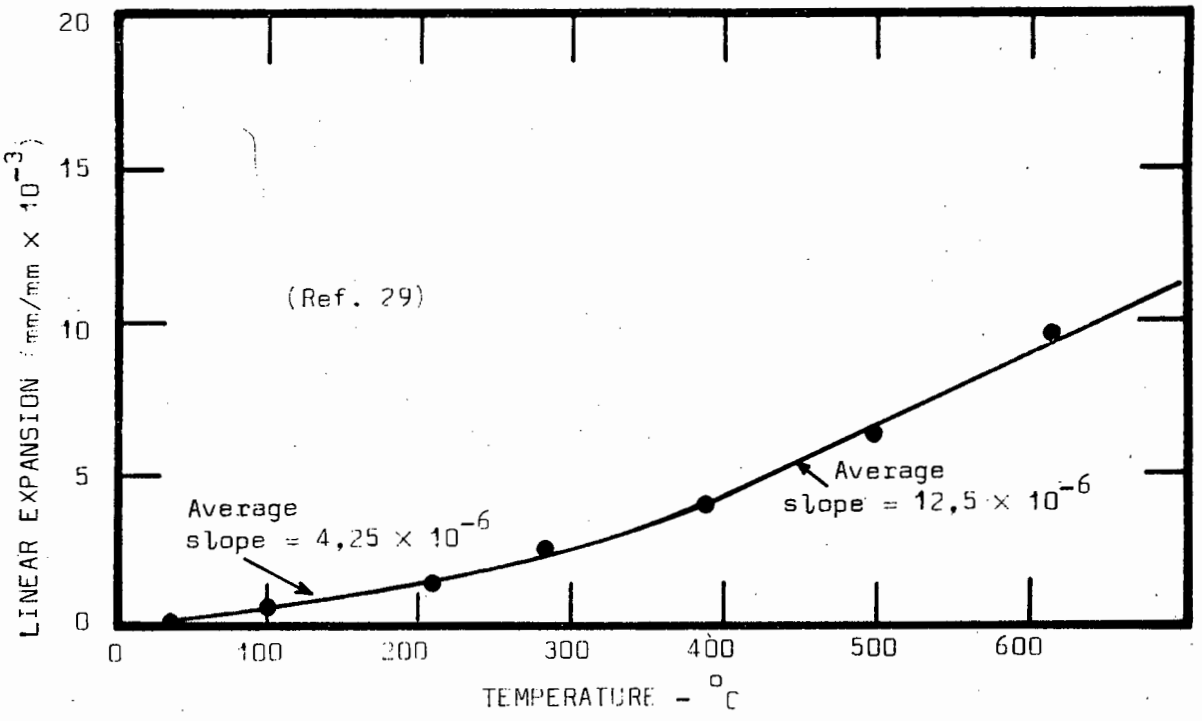

FIG.I.35: The linear expansion of concrete at elevated temperature.

CHAPTER 4 : THE EFFECTS OF DIFFERENTIAL EXPANSION OF THE CONSTITUENTS IN MORTAR AND CONCRETE

4.1 Durability at Normal Temperatures

The following durability investigations were all carried out on concrete heated within the range of temperature from $0^{o}C$ to $60^{o}C$. In these tests the concrete was either fully saturated, or maintained at high relative humidities, since none of the authors report permanent contraction of specimens, i.e. the water losses that occurred did not cause measurable shrinkage of the specimens.

Numerous investigators[41,42,43,44,47] have attributed the deterioration of physical properties and decrease in the durability of concrete to fracture of the mortar/coarse aggregate, and cement paste/aggregate, bond. The destruction of bond is thought to be caused by stresses resulting from the different thermal expansions of the constituents. Weiner[41] concludes that "the marked difference in durability between concrete made with siliceous gravel and trap-rock respectively (coarse aggregates), may be attributed to the influence of the thermal properties of the aggregate". Callan[42] too, is of the opinion that the coefficient of thermal expansion of aggregates has a major influence on the durability of concrete. The author[42] calculates that for a temperature change of $28^{o}C$, a difference in the expansion coefficient of 7×10^{-6} per deg C between mortar and coarse aggregate could result in tensile stresses of sufficient magnitude to cause cracking at the mortar/aggregate interface. Neville[30] points out that a large difference between the coefficients may not necessarily be detrimental to the concrete. This is because the differential movement is affected by other forces, such as those due to shrinkage. The author[30] indicates though, that when the two coefficients differ by more than $3,4 \times 10^{-6}$/deg C the durability may be affected.

There is not always agreement among investigators as to whether the above effect is real. Mitchell[45] concludes that 'other factors' probably influence the durability of concrete more than thermal incompatibility of the constituents. Walker *et al*[46] found that concretes having higher coefficients of expansion were less resistant to temperature changes than concretes with lower coefficients of thermal expansion. However, no relationship was found between the ability of concrete to withstand temperature changes and the difference between the thermal expansion

coefficients of aggregates and mortar. The authors conclude that "the deterioration of concrete during temperature changes appears to result from strains set up due to differences in temperature within the mass, rather than due to differences in thermal expansion coefficients".

4.2 The Effect of Elevated Temperature on the Thermal Incompatibility of Concrete Constituents

When cement mortar or concrete is exposed to elevated temperature, the observed volume change is a combination of the thermal expansion of the aggregate and complex hygrothermal volume changes of the cement paste. In the preceding chapter is is shown that cement paste, after initial expansion at low temperatures, exhibits considerable contraction as the temperature increases above 100°C. The rate of this contraction, and the magnitude, depends upon the rate and duration of heating at a particular temperature. In concrete or mortar, the contraction of the cement paste is overshadowed by the aggregate expansion, i.e. the linear deformation is a resultant of the length changes of cement paste and aggregate. In Fig. I.37 the coarse aggregate expansion, mortar expansion and combined expansion of these components, viz. that of concrete made with these constituents, is plotted against temperature[7]. From Fig. I.37 it is apparent that the thermal expansion of the mortar is greatly affected by the presence of coarse aggregate. In this regard Zoldners[40] indicates that the resultant curve of concrete expansion approaches that of the aggregate itself as the proportion of coarse aggregate to mortar increases.

The general manner in which the strain between paste and aggregate varies with temperature, can be plotted if idealized data are taken for the thermal movements of cement paste and aggregate respectively[39]. This is shown in Fig. I.38. According to Zoldners[40] this diagram indicates that at low temperatures the differential strains induce a small compressive stress in the cement paste. As the temperature increases, the compressive stress is reduced and changes to a much larger tensile stress. The relative strain between cement paste and aggregate after cooling, (also shown in Fig. I.38) indicate that by cooling the paste from these temperatures, even larger tensile stresses may occur[40].

It is interesting to calculate the respective magnitudes of the strains which may occur due to (i) incompatibility of thermal expansions, and (ii) shrinkage of the cement paste relative to aggregate. Assuming that

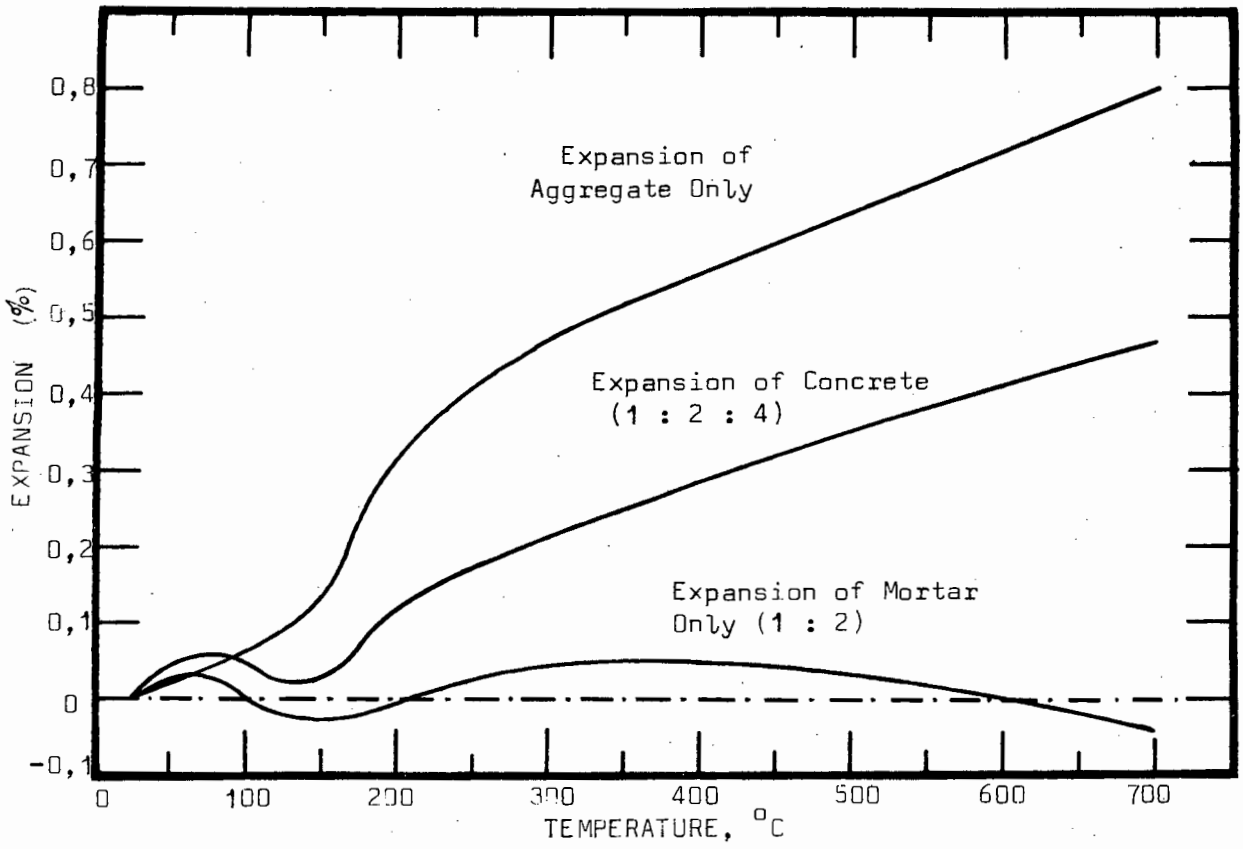

FIG. I.37: The linear deformation of andesite aggregate, mortar and a concrete incorporating the andesite aggregate and mortar.

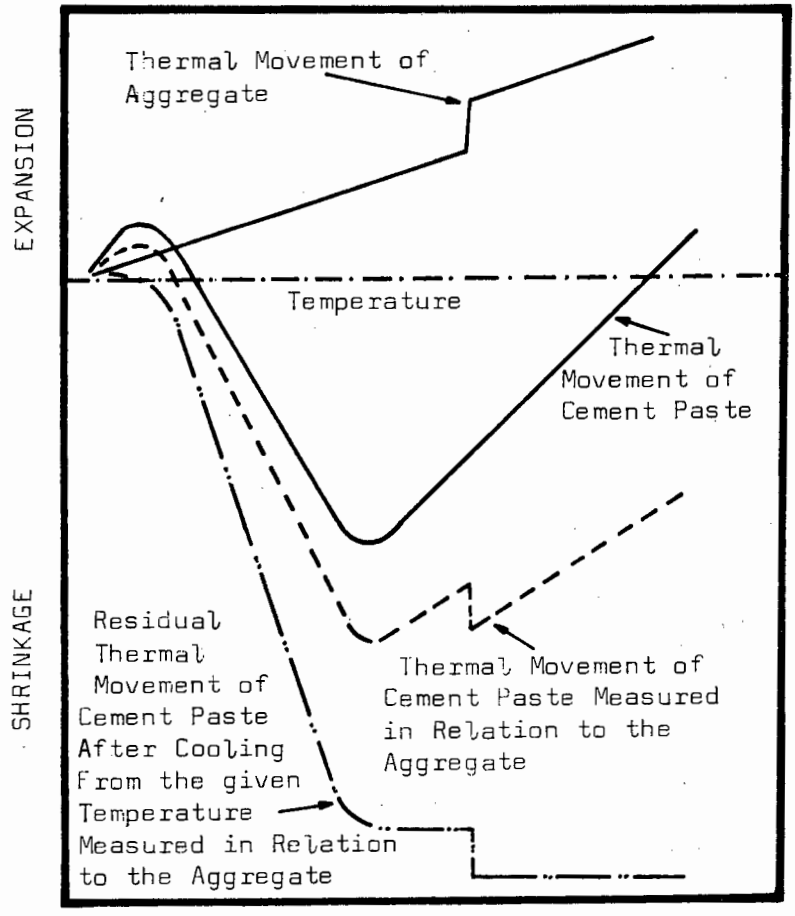

FIG. I.38: The thermal movement of a cement paste measured relative to a typical siliceous aggregate.

cement paste has a coefficient of thermal expansion of 14×10^{-6}/deg C* and coarse aggregate an expansion coefficient of 6×10^{-6}/deg C; for a temperature change of 80°C (from 20°C to 100°C, say) the strain caused by the difference in thermal expansions, ε_1, is

$$\varepsilon_1 = (14{,}0 - 6{,}0) \times 10^{-6} \times 80 \text{ mm/mm}$$
$$= 6{,}4 \times 10^{-4} \text{ mm/mm}$$
$$= 0{,}064\ \%$$

For the calculation of shrinkage strain between aggregate and paste, a shrinkage value of 0,145 percent is assumed for the paste at 100°C (see Fig. I.36). To this value, the coarse aggregate expansion must be added. Consequently,

$$\varepsilon_2 = 1450 \times 10^{-6} + 6 \times 10^{-6} \times 80 \text{ mm/mm}$$
$$= 0{,}145 + 0{,}048$$
$$= 0{,}193$$

From the above calculations it is apparent that the strain between the aggregate and paste due to shrinkage of the paste relative to the aggregate, is approximately three times greater than the strain which results from the incompatibility of the thermal expansions of these constituents. However, the stresses accompanying these strains may be of opposite sign, i.e. in the latter case the paste has expanded relative to the aggregate, while in the former case the paste underwent shrinkage relative to the aggregate. The prevailing opinion among concrete workers[40] concerning the interface stresses when paste shrinks relative to aggregate, is that such shrinkage results in radial compression at the interface and circumferential tension in the paste. The model behind this concept is an isolated aggregate particle surrounded by a thick shell of mortar or paste. Hsu[48] re-examined this simplified model and concluded that the imaginary thick shell of mortar (or paste does)not constitute a realistic concept. This is because the aggregate particles are close to each other and the aggregate/aggregate interaction should also be considered.

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* The value normally given in the literature.

4.3 The Analysis of Shrinkage Stresses in a Model of Hardened Concrete[48]

In order to investigate the internal shrinkage stresses which arise when mortar shirnks relative to coarse aggregate the following model was proposed[48]:

The aggregate is considered as made up of equal sized discs arranged regularly in a two-dimensional square pattern, the mortar occupying the voids between the discs. This is illustrated in Fig. I.39. The discs (coarse aggregate particles) are assumed infinitely rigid ($E = \infty$) and the mortar elastic.

Hsu[48] indicates that precise stress values cannot be expected from the above much simplified model. He maintained, however, that the model realistically reveals the correct nature of the stresses, i.e. whether tensile or compressive, and will give the right order of magnitude for their values. The method used for the analysis was a numerical point-matching method using the distance between aggregates as the variable parameter. This established the stresses as a function of the average distance between aggregates, d, where d is expressed as a function of the aggregate radius, r*.

The results of Hsu[48] for d = 0,5r; 0,1r; 0,2r and 0,4r respectively are shown in Fig. I.41. Stress coefficients for the normal stresses on the boundary OA2C (refer Fig. I.39) are given. The actual stress in the model is the product of the coefficient given in Fig. I.41, and the value X, where

$$X = \frac{1}{1000} \times \frac{E\,\epsilon}{1 - \mu}$$

where E = the modulus of elasticity of the mortar
μ = Poisson's ratio of the mortar
ϵ = the free shrinkage strain of the mortar

(A positive coefficient denotes tension caused by shrinkage of the mortar relative to the aggregate.)

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* In Fig. I.40 the average distance between aggregates (in terms of the radius r) is plotted against the degree of compactness[48]. The degree of compactness is defined as:

$$\frac{\text{Percentage Volume of Coarse Aggregate in Concrete}}{SC_{c.a.}}$$

where $SC_{c.a.}$ = solid content of the coarse aggregate
= Bulk density of coarse aggregate/Density of coarse aggregate

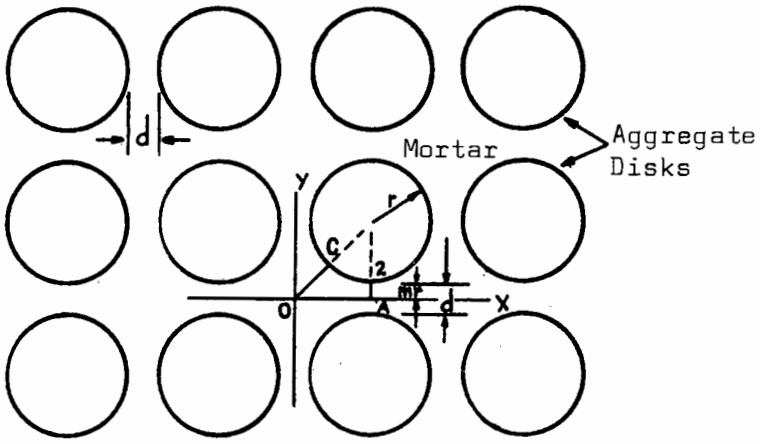


FIG. I.39: The two-dimensional model used in the stress analysis by Hsu[48].

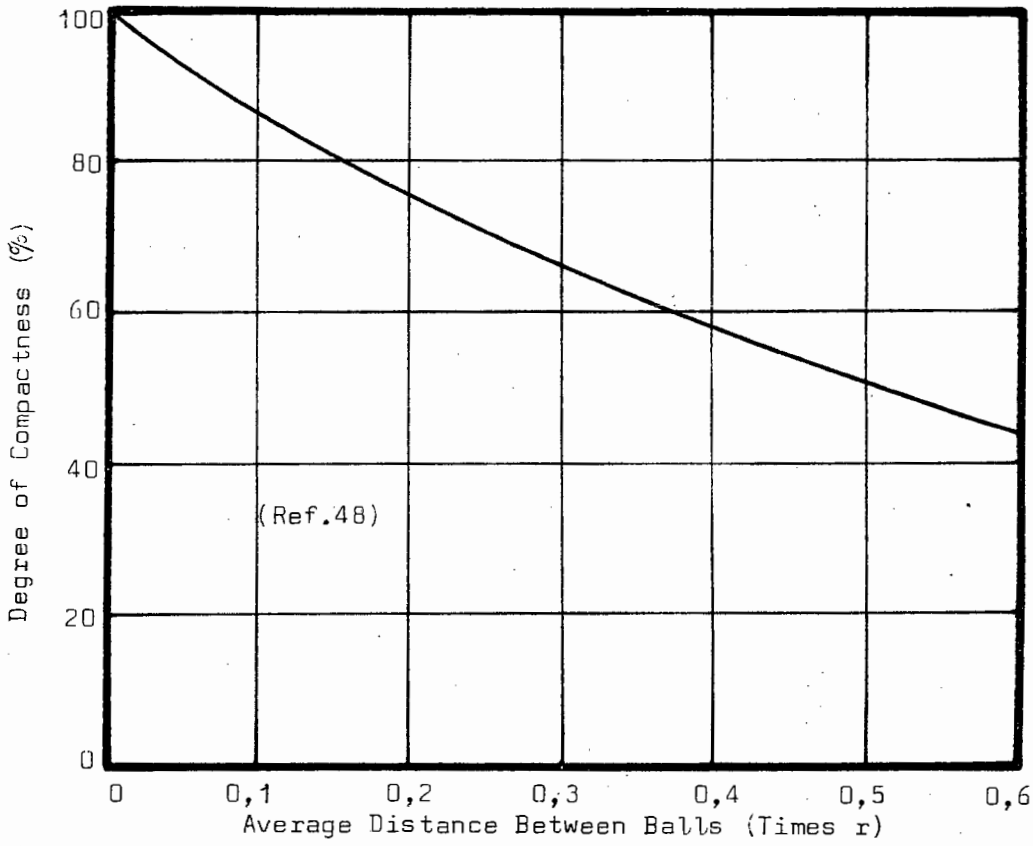
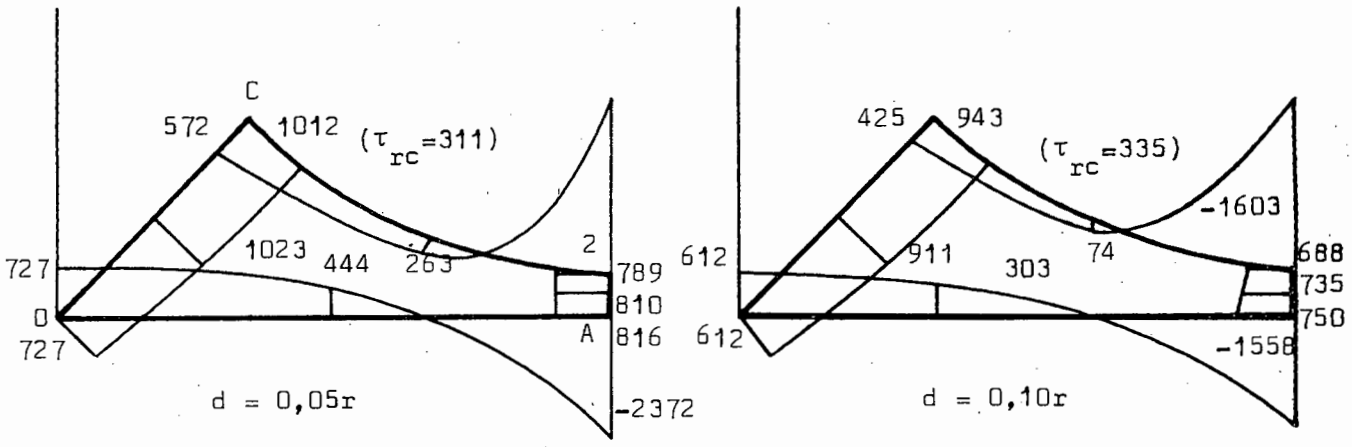


FIG.I.40: The relation between the degree of compactness and distance between equal size spherical aggregates arranged in face-centred cubic lattice.



Note: (1) +ve stress coefficient denotes tension.

(2) τ_{rc} is the shearing stress coefficient on the boundary

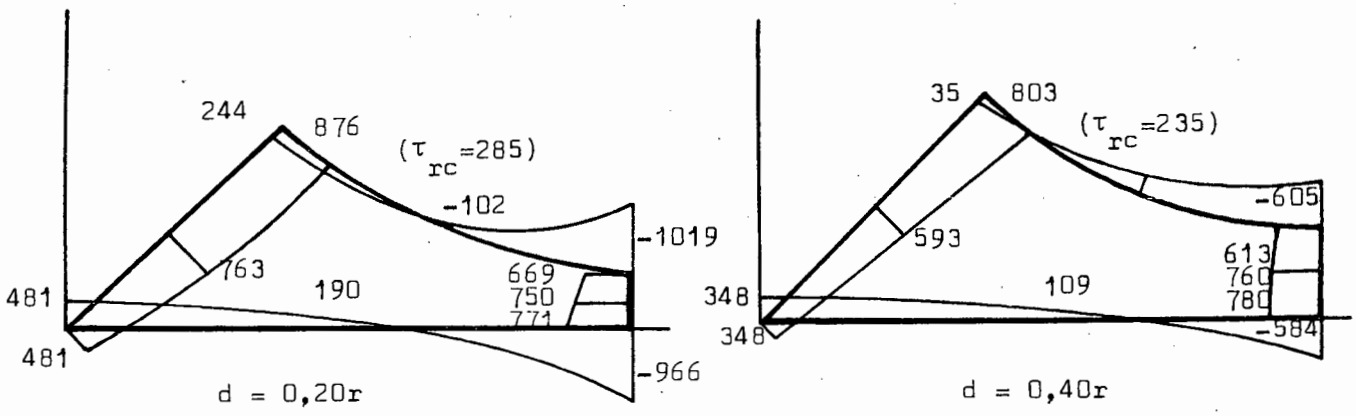


FIG.I.41: The normal stress coefficients on the boundary OA2C for different volumetric concentrations of aggregate. (The stress coefficients are for mortar shrinking relative to the coarse aggregate.)

Inspection of the coefficients given in Fig. I.41 show that when mortar shrinks relative to the coarse aggretage, tension as well as compression occurs in both the mortar and at the interface. Furthermore, the stresses are dependent upon the distance between the aggregates. This is illustrated in Fig. I.42; the stress coefficients for the maximum stresses in the mortar and at the interface respectively plotted as a function of the distance between aggregates. It is apparent that as the distance between the aggregates decreases both the maximum tensile and compressive stresses within the concrete increase.

It is worth mentioning that the correctness of the stress analysis was checked qualitatively by making actual models[48]. This model was made of sandstone discs arranged in a square array with cement paste between the discs; the cement paste was allowed to dry in air so as to induce shrinkage. It was found[48] that for distances between discs of 0,4 r and 0,15 r respectively, the cracking pattern of the paste corresponded precisely to the stress analysis.

Hsu[48] estimates the order of actual tensile <u>bond</u> stress due to a mortar drying shrinkage strain of 12×10^{-4} mm/mm. Assuming E_{mortar} = 34,5 GPa (5×10^{6} psi), μ_{mortar} = 0,2 and the distance between aggregates, d = 0,2; the maximum elastic bond stress is:

$$\sigma = \frac{C}{1000} \times \frac{E\,\epsilon}{1 - \mu}$$

$$= \frac{244}{1000} \times \frac{12 \times 10^{-4}}{1 - 0,2} \times \frac{34,5}{1} \times \frac{10^{9}}{10^{6}}$$

$$= 12,62 \text{ MPa (1830 psi)}$$

This is 5 to 15 times greater than the maximum mortar/aggregate tensile bond strength obtained experimentally[49]. Hsu[48] indicates that the analysis may give exaggerated values since two effects which will reduce the stress are neglected in the analysis. They are:

(i) The aggregates are elastic, rather than rigid as assumed in the analysis; and

(ii) The effect of creep; this could reduce the stresses significantly.

The author[48] concludes, though, that the stress is sufficiently large to make it significant in spite of these factors.

The above analysis was carried out assuming the mortar to shrink relative to the aggregate. In the case of expansion of the mortar relative to the aggregate particles, it is only necessary to change the sign of the values in Figs. I.41 and I.42. In this case the maximum tensile stresses in both the mortar and at the mortar/aggregate interface are several times greater than the tensile stresses which result from shrinkage of the mortar.

4.4 Calculation of the Stresses caused by Differential Expansion of the Constituents of Concrete at Elevated Temperature

It must be pointed out that although the above analysis is for mortar shrinking relative to coarse aggregate, the stresses due to:

(i) The incompatibility of both the fine aggregate and coarse aggregate expansion with the cement paste expansion; and

(ii) shrinkage of the cement paste relative to both the fine aggregate and the coarse aggregate may also exert a significant effect on the properties of heated concrete.

The fine aggregate/paste effect becomes clear from the stress analysis by Hsu[48]. Consider the mortar between the voids of the coarse aggregate particles. The mortar usually has a cement/sand ratio of between 1 : 2 and 1 : 3. (This ratio may be as large as 1 : 4 in some instances, depending upon factors like the w/c ratio and the workability of the concrete mix.) It has been shown[48] that a good estimate of the clear distance between sand particles for mortar with a 1 : 3 proportion and w/c ratio of 0,55 is 0,45r, where r is the average radius of the sand particles. For mortar with a cement/sand proportion of 1 : 2 and w/c ratio of 0,55 the clear distance between sand particles is 0,2r. From Fig. I.42, the internal stresses caused by differential volume change of the sand and cement paste at these spacings can be determined. It is apparent that for a clear distance between sand particles of 0,45r, the resulting stresses may be up to two times greater than the stresses for a sand spacing of 0,2r.

Furthermore, it should be remembered that the mortar is bonded to the coarse aggregate by a layer of hydrated cement. The relative expansions of cement

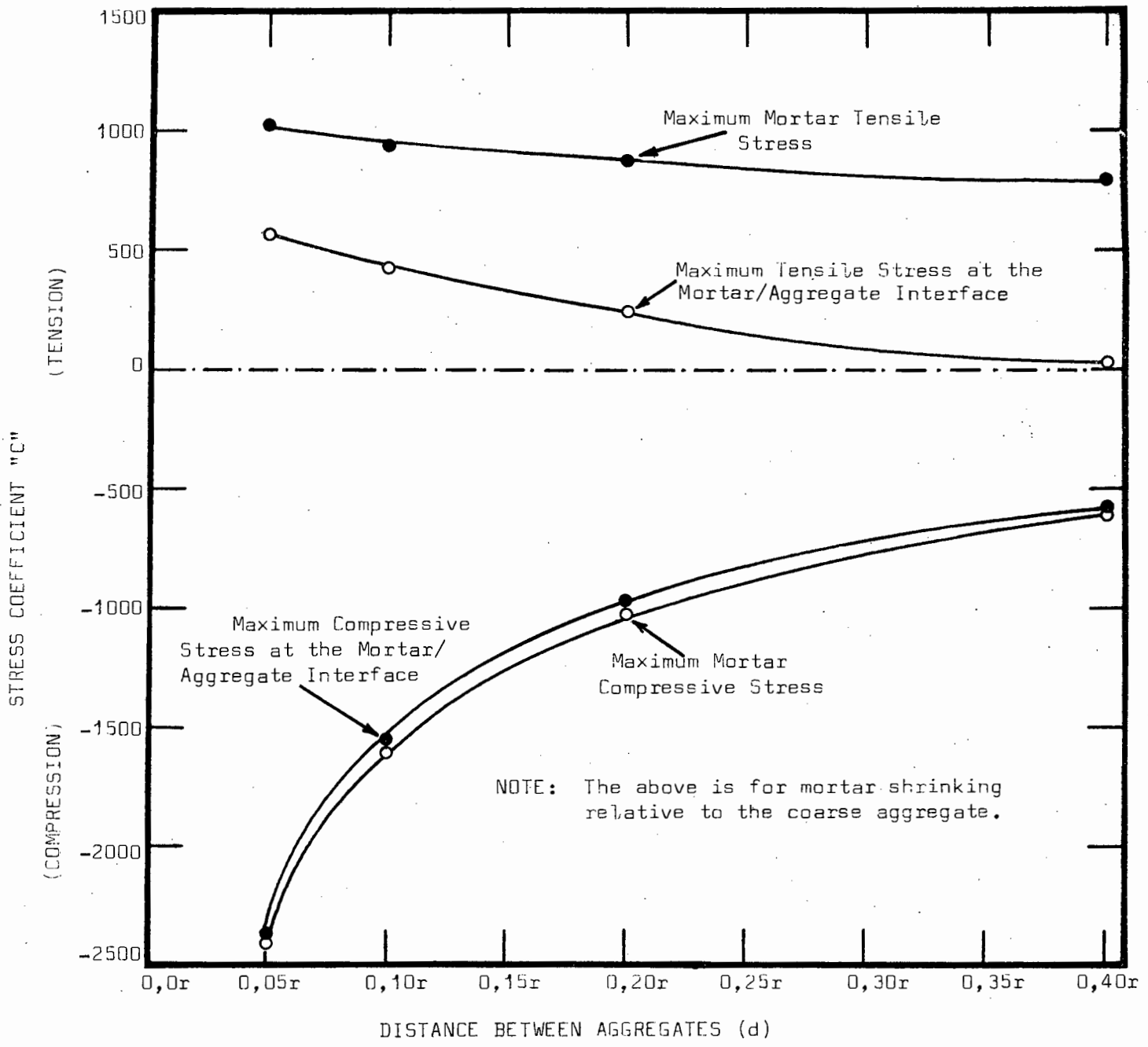


FIG. I.42: The stress coefficients for the maximum stresses in the mortar and at the mortar/coarse aggregate interface, plotted as a function of the distance between the coarse aggregate particles.

paste and coarse aggregate may thus modify the stresses in the vicinity of the coarse aggregate particle. This is not taken into account in the stress analysis.

Consequently, it appears that the stresses caused by differential movement of the constituents in heated concrete depend upon:

(i) The volumetric concentration of the coarse aggregate.

(ii) The volumetric concentration of the fine aggregate.

(iii) The thermal expansion of the coarse aggregate.

(iv) The thermal expansion of the fine aggregate.

(v) The thermal expansion of the mortar.

(vi) The thermal expansion of the cement paste.

(vii) The shrinkage of the mortar relative to the coarse aggregate.

(viii) The shrinkage of the cement paste relative to the aggregate.

The nature of the resulting stresses, and whether the maximum stresses will be caused by the strain between (a) the mortar and coarse aggregate; or (b) the cement paste and aggregate, depends upon the relative magnitudes of (i) to (viii).

An indication of the internal stresses that theoretically may occur when concrete is heated to elevated temperature, can be obtained by applying the method proposed by Hsu[48] to a nominal 1 : 2 : 4 concrete mix having a w/c ratio of 0,60. It is assumed that the coarse and fine aggregates are both sandstone and that (i) the sandstone has thermal expansion[26,27] ccefficients within different temperature ranges as given in Table I.6, and (ii) the thermal expansion of neat cement paste is 14×10^{-6}/deg C.

TABLE I.6

Thermal Expansion Coefficients of Sandstone within Different Temperature Ranges[26].

Temperature Range ^{o}C	Thermal Expansion Coefficient $\times 10^{-6}$/deg C
20 - 100	10,0
100 - 300	15,0
300 - 500	21,5

For the given mix proportions, the average distance between coarse aggregate particles and between fine aggregate particles, respectively, may be approximated. These are both of the order of 0,2r. Consequently, in the hypothetical example the highest stresses will probably occur as a result of the strain between the cement paste and fine aggregate. This is because:

(i) The volumetric concentration of coarse aggregate particles is the same as the volumetric concentration of the fine aggregate particles; and

(ii) The difference between the cement paste expansion and the aggregate expansion will always be larger than the difference between the mortar expansion and coarse aggregate expansion. (A result of having similar coefficients of expansion for coarse and fine aggregate.) Furthermore, the cement paste shrinkage is far greater than that of the mortar, i.e. the strain due to shrinkage of the paste relative to the fine aggregate is greater than the strain due to shrinkage of the mortar relative to the coarse aggregate.

It must be emphasized though, that the maximum stresses will not always necessarily occur as a result of the strain between the cement paste and aggregate; it depends on the relative magnitudes of the various volumetric concentrations and expansion coefficients.

For the average distance between fine aggregate particles of 0,2r, the following stress coefficients can be determined from Fig. I.42:

(i) For the case where the paste expands relative to the fine aggregate:

(a) Maximum paste tensile stress coefficient = 1019

(b) Maximum paste/fine aggregate interface tensile stress coefficient = 985

(c) Maximum paste compressive stress coefficient = 876

(d) Maximum paste/fine aggregate interface compressive stress coefficient = 244.

(ii) For the case where the paste undergoes shrinkage relative to the fine aggregate:

(a) Maximum paste tensile stress coefficient = 876

(b) Maximum paste/fine aggregate interface tensile stress coefficient = 244

(c) Maximum paste/compressive stress coefficient = 1019

(d) Maximum paste/fine aggregate interface compressive stress coefficient = 985

For the particular concrete under consideration, the above two cases could both occur for heating in the unsealed condition. As the concrete is heated to the required temperature, the cement paste having a larger expansion coefficient than the fine aggregate, expands relative to the fine aggregate. If sufficient shrinkage of the cement paste occurs, the paste reverses the former 'expansion relative to the fine aggregate' to a 'contraction relative to the fine aggregate'. However, it could happen that at certain temperature levels the initial expansion of the paste relative to the fine aggregate is lower than the initial expansion of the cement paste. This is because the thermal expansion coefficient of the fine aggregate increases with temperature, i.e. as the temperature levels increase, the thermal expansion coefficient of the fine aggregate becomes larger than the coefficient of thermal expansion of the cement paste.

When the concrete under consideration remains fully saturated during heating, only expansion of the cement paste relative to the fine aggregate occurs. This does not change since there is no shrinkage of the cement paste.

For calculating the stresses in the cement paste and at the paste/sand interface, only the two worst cases are considered, viz.

(i) When the paste expands relative to the fine aggregate at temperatures of 70°C and 100°C*, and no loss of water occurs.

(ii) When the paste shrinks relative to the fine aggregate, at temperatures of 70°C, 100°C, 150°C, 250°C and 400°C

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* Insufficient data are available to enable calculation of the stresses under this condition at higher temperatures, i.e. Young's modulus and Poisson's ratio have not been determined on sealed specimens heated to higher temperatures.

In Table I.7 the theoretical values of both tensile and compressive stresses which may occur both at the cement paste/fine aggregate interface, and within the cement paste, are given. In computing these stresses, values for free shrinkage of the paste at different temperature levels were taken from work by Harada[7]. The given values of E_{paste} and μ_{paste} are from dynamic determinations of these properties on a cement paste after slow cooling from the indicated temperatures. The paste had a w/c ratio of 0,26 and the heating time at all temperatures was approximately 24 hours. These values are from unpublished work[50] done in this laboratory.

It is apparent from Table I.7 that the calculated values of the tensile stresses, both within the paste and at the paste/aggregate interface, are far greater than what a Portland cement paste can withstand; in some instances the calculated value of tensile stress is more than an order of magnitude greater. Also at temperatures above 100°C the calculated values of compressive stress become much larger than the values normally associated with the uniaxial compressive strength of concrete. However, since the triaxial compressive strength of concrete is much greater than uniaxial strength, compressive stresses of this magnitude could possibly be accommodated by the paste. Furthermore, it is possible that these results are exaggerated, since:

(i) The aggregates are elastic rather than rigid, as assumed in the stress analysis.

(ii) The sand grains are separated[37] from the surrounding cement by air films, and in many cases extending nearly all around the grain. Hence some considerable movement of the sand grain can take place before contact is made with the cement paste and the stressing action comes into play.

(iii) The cement paste is not simply elastic, but creeps; both specific creep and creep rate usually being higher at elevated temperature than at room temperature.

The above effects would reduce the calculated value of the stress within the concrete. However, it seems probable that in certain instances the tensile stresses will be of sufficiently great magnitude to cause microcracking within the concrete.

TEMPERATURE	EXPANSION OF FINE AGG.* mm/mm	EXPANSION OF CEMENT PASTE* mm/mm	SHRINKAGE OF CEMENT PASTE (ref 7) mm/mm	Δ STRAIN BETWEEN PASTE AND FINE AGG. = ϵ mm/mm	E_{paste} (ref 50) GPa	μ_{paste} (ref 50)	$X = \frac{\epsilon E}{(1-\mu)} \times \frac{1}{1000}$ MPa	MAX. PASTE TENSILE STRESS = "C" × X MPa	MAX. INTERFACE TENSILE STRESS = "C" × X MPa	MAX. PASTE COMPRESSIVE STRESS = "C" × X MPa	MAX. INTERFACE COMPRESSIVE STRESS = "C" × X MPa
70° Sealed	$4,5 \times 10^{-4}$	$6,30 \times 10^{-4}$		$1,8 \times 10^{-4}$	25,0	0,320	$6,62 \times 10^{-3}$	6,75	6,52	5,80	1,62
100° Sealed	$7,5 \times 10^{-4}$	$10,5 \times 10^{-4}$		3×10^{-4}	24,5	0,303	$10,55 \times 10^{-3}$	10,75	10,39	9,24	2,57
70° Dry	$4,5 \times 10^{-4}$	$6,30 \times 10^{-4}$	$10,0 \times 10^{-4}$	$8,2 \times 10^{-4}$	18,50	0,360	$23,70 \times 10^{-3}$	20,76	5,78	24,15	23,34
100° Dry	$7,5 \times 10^{-4}$	$10,50 \times 10^{-4}$	$15,0 \times 10^{-4}$	$12,0 \times 10^{-4}$	16,25	0,351	$30,05 \times 10^{-3}$	26,32	7,33	30,62	29,59
150° Dry	$18,75 \times 10^{-4}$	$17,5 \times 10^{-4}$	$17,5 \times 10^{-4}$	$18,75 \times 10^{-4}$	17,00	0,336	$48,01 \times 10^{-3}$	42,05	11,72	48,92	47,29
250° Dry	$33,75 \times 10^{-4}$	$31,50 \times 10^{-4}$	$24,5 \times 10^{-4}$	$26,75 \times 10^{-4}$	12,40	0,380	$53,50 \times 10^{-3}$	46,86	13,06	54,51	52,70
400° Dry	$80,63 \times 10^{-4}$	$52,50 \times 10^{-4}$	$33,0 \times 10^{-4}$	$61,13 \times 10^{-4}$	9,50	0,411	$98,61 \times 10^{-3}$	86,13	24,06	100,49	97,13

"C" is the stress coefficient from Figure I.42

TABLE I.7: Values of the tensile and compressive stresses which may theoretically occur at the cement paste/fine aggregate interface and within the cement paste.(48).

CHAPTER 5 : SUMMARY OF THE LITERATURE REVIEW AND CONCLUSIONS BASED ON THE REVIEW

5.1 The Structural Behaviour of Concrete at Elevated Temperature

The literature review shows that:

(i) The compressive strength of both sealed and unsealed concrete is reduced when concrete is subjected to elevated temperature. In general, the higher the temperature the greater the reduction in compressive strength; at 400^{o}C, compressive strengths of 50 percent of the unheated reference strength are not uncommon. Sealed specimens usually undergo greater reduction in compressive strength than unsealed specimens; the difference between the heated compressive strength of sealed and unsealed specimens may be as large as 40 percent of the unheated reference strength. In some instances, an increase in the compressive strength of unsealed specimens, (i.e. an increase w.r.t. the unheated reference strength) at temperatures between 150^{o}C and 250^{o}C has been observed. The increase in strength was of the order of 10 to 25 percent of the unheated reference strength. Sealed specimens did not have increased strengths at any temperature level.

(ii) The flexural strength of concrete is more affected by heating than the compressive strength; the flexural strength at 400^{o}C may be as low as 40 percent of the unheated reference strength. Sealed specimens exhibit between 20 and 30 percent greater reduction in flexural strength than unsealed specimens. The behaviour of flexural strength at elevated temperatures does not only differ from compressive strength in the extent of the deterioration; in unsealed concrete at temperatures between 150^{o}C and 250^{o}C, the flexural strength never increased above the reference strength when an increase in compressive strength occurred.

(iii) The Young's modulus (both static and dynamic) of concrete is more adversely affected by exposure to elevated temperature than either the compressive strength or the flexural strength. The higher the temperature the greater the reductions in Young's modulus; at 400^{o}C reductions of 85 percent in Young's modulus have been reported.

Some investigators attribute the reductions in Young's modulus of heated concrete to the loss of water from the gel pores and capillary pores, the water loss being considered as the removal of an incompressible phase from within the concrete. However, sealed concrete specimens exhibit reductions in Young's modulus similar to, if not greater than, the reductions in Young's modulus of unsealed specimens at the same temperature. Since water is not lost from sealed specimens during heating, the behaviour of Young's modulus in sealed specimens is attributed to a chemical change within the hydrated cement. The chemical change results in the formation of a physically weaker matrix and consequently a reduction in Young's modulus.

(iv) Poisson's ratio (determined both dynamically and from strain measurement) in unsealed concrete is usually reduced by exposure to elevated temperatures. One investigator indicates that the higher the temperature, the greater the reduction in Poisson's ratio: at 400^{o}C, a Poisson's ratio of 40 percent of the unheated value was found. However, conflicting results are reported for the values of Poisson's ratio in the range of temperature from 300^{o}C to 500^{o}C. In another investigation, it was found that at these temperatures Poisson's ratio increased w.r.t. the unheated value of Poisson's ratio; the higher the temperature, the greater the increase in Poisson's ratio. In sealed concrete, Poisson's ratio has been investigated only at temperatures up to 100^{o}C. These results indicate that Poisson's ratio in sealed concrete is not influenced by long-term exposure to temperatures up to 100^{o}C.

(v) The ultrasonic velocity of unsealed concrete is always reduced when concrete is heated. At 400^{o}C the losses in ultrasonic pulse velocity are between 30 and 50 percent of the pulse velocity prior to heating. The general behaviour of pulse velocity is not dissimilar to that exhibited by Young's modulus. However, at a particular temperature the reduction in pulse velocity is not as large as the reduction in Young's modulus.

(vi) The creep of concrete is usually higher at elevated temperature than at room temperature. For unsealed concrete, the creep at 50^{o}C is two to three times greater than the creep at room temperature. At 400^{o}C, creep may be as great as ten times the creep at room

temperature. However, some controversy exists as to whether the creep at temperatures around 100°C is greater than the creep at temperatures between 50°C and 70°C. Sealed and unsealed concrete specimens exhibit approximately the same creep at temperatures up to 100°C, although there appears to be a tendency for unsealed specimens to creep more than sealed specimens. No data for the creep of sealed concrete at temperatures above 120°C have been reported.

The creep rate of concrete also increases at elevated temperature. Most investigators agree to a definite maximum for the creep rate at temperatures between 50°C and 80°C, the creep rate being two to three times higher than the creep rate at room temperature. A corresponding minimum creep rate is reported at temperatures around 100°C, the creep rate being only slightly higher, and in some instances lower, than the creep rate at room temperature. One investigator, however, reports that at 100°C a maximum creep rate occurs in sealed specimens. The creep rate at temperatures above 100°C has only been determined on unsealed specimens. It was found that above 100°C the creep rate increases as the temperature increases; at 400°C the creep rate was more than three times the creep rate at room temperature.

An interesting observation regarding the creep of concrete at elevated temperature is that concrete exhibits no creep, or very little creep, if the creep is measured at a temperature below that at which the evaporable water was removed. Also, it was found that the creep recovery of concrete subjected to elevated temperature in independent of temperature.

5.2 The Influence of Certain Experimental Variables and Test Conditions on the Behaviour of Concrete at Elevated Temperature

The reviewed literature indicates that:

(i) The structural properties of concrete at high temperature are related to the type of aggregate that is used in the concrete. Some investigators propose that this effect is due to incompatibility of the thermal expansion coefficient of the aggregate with that of

the cement paste. However, this has not been conclusively established. The fact that two different aggregate types, with similar thermal expansion characteristics, resulted in different property behaviour of the concrete in which they were respectively used, suggests that factors such as surface texture, shape of aggregate and volumetric concentration of aggregate may also influence the behaviour of concrete made with a particular aggregate type.

It is particularly noticeable from the literature reviewed that many investigators have neglected the fact that the fine aggregate may influence the behaviour of concrete at elevated temperatures. In this regard it was shown in a theoretical stress analysis, that the stresses which may result from differential movement of concrete constituents, i.e. mortar and coarse aggregate, and cement paste and fine aggregate, respectively, are dependent upon the spacing between aggregate particles, and not on the size of the aggregate particles.

(ii) Concrete mix proportions exert an influence on the structural behaviour of concrete at high temperatures. The respective effects of the w/c ratio and the a/c ratio on the property behaviour of heated concrete have not been conclusively determined. Results are reported which indicate that weaker mixes undergo less relative reduction in compressive strength than stronger concrete mixes. However, there is not agreement on this conclusion; other investigators believe the converse to be true.

(iii) The structural properties of concrete measured whilst hot may be different to those determined on a similar specimen which has been cooled to room temperature before testing. In general, sealed concrete exhibits better property behaviour when cooled to room temperature before testing than when tested hot. Conflicting findings regarding the behaviour of unsealed specimens tested under these two conditions have been reported. However, it appears that the structural properties of unsealed specimens tested hot are not significantly altered by cooling the specimens.

(iv) Concrete which is allowed to cool to room temperature after heating, if left sufficiently long, recovers to a certain extent the property reduction that was caused by heating. It is particularly interesting to note that in some instances these increases occurred despite the fact that the concrete contained no water in either the capillary pores or gel pores.

5.3 The Thermal Expansion of Concrete, and Expansion of the Individual Constituents, at Elevated Temperature

5.3.1 Thermal Expansion Behaviour

The literature reviewed indicates that the thermal expansion of concrete is a resultant expansion of the individual constituents, i.e. aggregate and cement paste.

The coefficient of thermal expansion of most aggregates appears to increase at elevated temperature; at temperatures around 400°C the coefficient may be between 2 and 6 times larger than the coefficient at 100°C. However, the reported literature does not indicate to what extent the thermal expansion of aggregates are reversible at temperatures up to 400°C, i.e. to what extent permanent dilation of the aggregate occurs.

The coefficient of thermal expansion of both sealed and unsealed cement paste is affected by hygrothermal volume change of the paste during heating. Sealed paste usually has a lower coefficient of thermal expansion than unsealed paste; respective values of $11{,}6 \times 10^{-6}$/deg C and 25×10^{-6}/deg C have been reported[9]. However, the coefficient of thermal expansion of unsealed paste depends on the moisture content of the paste; a completely dry paste may have a thermal expansion approximately the same as that of sealed paste. Furthermore, in unsealed paste the loss of water at elevated temperature, apart from resulting in an increase in the coefficient of thermal expansion, causes shrinkage of the paste. Shrinkage of cement paste having a w/c ratio of 0,60 may be as large as 1 percent at 250°C. The extent of the shrinkage that occurs depends on the temperature level and the exposure at the temperature.

The coefficient of thermal expansion of different concretes may therefore be widely different, the coefficient depending on aggregate type; temperature level; mix proportions; water content and whether the concrete is sealed or

unsealed during heating. Values of the coefficient of thermal expansion range from between 5 X 10^{-6}/deg.C to 15 X 10^{-6}/deg.C.

5.3.2 The Effect of Differential Expansion of Concrete Constituents

A theoretical assessment of the stresses which result from differential expansion of mortar and coarse aggregate indicates that:

(i) Both compressive and tensile stresses occur, at both the mortar/coarse aggregate interface and within the mortar.

(ii) The magnitude of these stresses depends upon the extent of the differential movement between the mortar and the coarse aggregate particles, the volumetric concentration of the coarse aggregate, and the modulus of elasticity and Poisson's ratio of the mortar. However, the magnitude of the stresses does not depend on the size of the aggregate particles.

(iii) When mortar undergoes an expansion relative to aggregate particles the tensile stresses are of greater magnitude than those which occur when mortar undergoes shrinkage relative to aggregate particles.

(iv) The stresses which result from incompatible expansion/shrinkage may be of sufficiently great magnitude to cause microcracking within the concrete. It is possible, though, that in many instances the stresses are significantly reduced by creep.

Of particular interest in the abovementioned stress analysis is the fact that the magnitude of the stresses caused by differential expansion (or by differential shrinkage) does not depend on the size of the aggregate particles. This suggests that the stresses due to;

(i) incompatibility of the fine aggregate thermal expansion with the cement paste thermal expansion, and

(ii) shrinkage of the cement paste relative to the fine aggregate,

may also exert a significant effect on the structural properties of concrete at elevated temperatures.

5.4 The Proposed Investigation

From the foregoing literature review it becomes clear that the structural properties of heated concrete may depend on the heating time at a particular temperature level: for specimens which remain saturated during heating the stresses resulting from differential expansion of the constituents may be relieved by creep; for test specimens which are allowed to dry during heating, the stresses resulting from either differential expansion or from shrinkage may be relieved by creep, or progressive microcracking may occur within the concrete. Furthermore, water loss from unsealed test specimens may affect properties other than only the shrinkage, e.g. Gilkey[73] established that concrete specimens gently air-dried before testing can exhibit ultimate compressive strength between 20% and 30% greater than the compressive strength of saturated specimens. Also, it should be remembered that time dependent chemical reactions may occur within the concrete. These may be of a beneficial nature, e.g. heat stimulated cement hydration, or reactions which may be detrimental to the structural properties e.g. the conversion of existing hydrates to hydrates of lower strength. The chemical reactions may be of particular importance in instances where sufficient water is available for reaction, i.e. in sealed concrete, and in unsealed concrete at temperature levels where the removal of evaporable water is relatively slow.

In the reviewed literature regarding the testing of concrete properties at elevated temperatures, it is apparent that the various investigators did not always use the same heating time. In some instances tests were performed immediately that the desired temperature level was attained, while in other instances the test specimens were maintained at the test temperature for periods which ranged from a few hours to a few days. It is thought that the different heating times adopted by different investigators could be partly responsible for the wide variation between reported results and differences of opinion regarding these results. It is apparent also that in much of the research the reduction in the structural properties of concrete is attributed to weakening/failure of the bond between the mortar and coarse aggregate: in most instances the investigators did not take into consideration the fact that stresses at the cement paste/fine aggregate bond could be responsible for the deterioration in structural properties.

The purpose of the following investigation is to determine for both sealed and unsealed concrete and mortar test specimens heated to various temperature levels:

(i) The effect of heating time on the linear deformation and some

physical properties of concrete and mortar

(a) during heating

(b) after cooling from test temperature, and

(c) after cooling from the test temperature and a period of re-immersion in water.

(ii) Whether microcracking within test specimens is a significant factor in affecting the structural behaviour of concrete and mortar at elevated temperature.

(iii) Whether the coarse aggregate in concrete test specimens is necessarily detrimental to the structural behaviour of heated concrete.

(iv) For a particular $^{w}/_{c}$ ratio, whether a change in the volumetric concentration of aggregate (within limits of practibility *) affects the structural behaviour of concrete and mortar at elevated temperature; and for a particular $^{a}/_{c}$ ratio, whether a change in the water content of a mix (within the limits of practibility *) affects the structural behaviour of concrete and mortar at elevated temperature.

For the experimental results obtained as under (i) above it may be possible to relate changes in the structural properties of concrete and mortar specimens to the behaviour of linear deformation and residual linear deformation ** of test specimens at the various temperature levels. Furthermore it will be of interest to compare, for the structural properties, the variation caused by the heating time to the variation which results from having different mix proportions which differ as in (iii) above.

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* The workability of the mix has to be considered.

** The residual linear deformation is determined on test specimens after cooling on the datum temperature.

PART II

EXPERIMENTAL DETAILS

CHAPTER 1 : MATERIALS

1.1 Cement

Ordinary Portland cement of South African manufacture was used in this investigation. The cement was purchased in a single lot on the open market, thoroughly blended, and stored in airtight steel containers.

The chemical analysis and physical properties of the cement were determined in accordance with S.A.B.S. 471, both at the beginning and towards the end of the mixing programme. The results of these tests are given in Tables II.1 and II.2. These data indicate that there is no significant difference between the results of the two series of tests.

TABLE II.1

The Chemical Analysis and Compound Composition of Cement* at the Beginning and at the End of the Mixing Programme

Chemical Analysis (%)			Compound Composition (%)		
	At Beginning	At End		At Beginning	At End
SiO_2	21,9	22,2	C_3S	46,2	46,8
Al_2O_3	6,2	5,8	C_2S	24,8	25,3
Fe_2O_3	2,8	2,9	C_3A	11,7	10,4
CaO	64,1	64,0	C_4AF	8,5	8,8
MgO	1,3	1,4	$CaSO_4$	3,1	2,9
SO_3	1,8	1,7	CaO free	1,4	1,3
Ignition Loss	1,7	1,7	MgO	1,3	1,4
			Insoluble Residue	1,1	1,1
			Ignition Loss	1,7	1,7
Total	99,8	99,7	Total	99,8	99,7

* Chemical analysis and physical tests by National Portland Cement Company Limited, Philippi, Cape.

TABLE II.2

Physical Test Resulst of Cement at the Beginning and at the End of the Mixing Period.

Test Performed	At Beginning	At End
Specific Surface Area:	2792 cm^2/g	2791 cm^2/g
Le Chatelier Expansion:	1 mm	1 mm
Initial setting time:	155 min	155 min
Final setting time:	215 min	235 min
Water used:	26%	26%
Room temperature:	21°C	20°C
Compressive Strength: 3 days	30,6 MPa	30,1 MPa
(10% water used): 7 days	44,5 MPa	44,2 MPa

1.2 Fine Aggregate

The fine aggregate was a natural siliceous sand (Cape Flats sand) purchased in a single consignment. Batches of sand were dried weekly in a purpose-made oven and the moisture content of each batch of sand determined after drying. When the sand was completely dry it was placed in airtight steel containers until used.

The sand had a density of 2660 kg/m^3, a bulk density of 1763 kg/m^3 and a Fineness Modulus of 1,76; the results of a typical grading analysis are shown in Table II.3. In Table II.4 the chemical composition of the sand is given.

TABLE II.3

A Typical Grading Analysis of the Sand Used in this Investigation.

Sieve No. (Tyler Series)	Percentage Retained
8	0
14	0
28	12
35	29
48	66
60	76
100	97,9
200	99,8

TABLE II.4

Chemical Composition of the Sand Used in this Investigation

Oxide	Percentage
SiO_2	73,33
CaO	13,07
Al_2O_3	10,39
MgO	0,16
K_2O	0,19
Fe_2O_3	8,11
H_2O	0,09
Ignition Loss at 1050°C	1,07
	98,41

1.3 Coarse Aggregate

The coarse aggregate was a crushed quartzite (Malmesbury quartzite) graded to -18,85 mm + 9,42 mm. A typical grading analysis and the chemical composition of the coarse aggregate is given in Tables II.5 and II.6 respectively. The aggregate was of angular shape and rough surface texture, and had a density and bulk density of 2710 kg/m^3 and and 1611 kg/m^3 respectively.

TABLE II.5

Grading Analysis of Coarse Aggregate (Malmesbury Quartzite)

Sieve Size (Tyler Series) mm	Percentage Retained
18,85	0
13,33	56
9,42	100

TABLE II.6

The Chemical Analysis of the Coarse Aggregate

Oxide	Percentage
SiO_2	74,14
Al_2O_3	11,87
K_2O	3,04
FeO	3,11
Fe_2O_3	0,61
TiO_2	0,61
MgO	1,39
CaO	1,24
Na_2O	2,11
Ignition Loss at 1050°C	0,67
	98,39

CHAPTER 2 : MANUFACTURE OF TEST SPECIMENS

2.1 Mix Proportions

The mix proportions (by weight) of the various mixes used in this investigation are given in Table II.7. A total of six mixes were used, three concrete mixes and three mortar mixes. The mortar mixes differed from the respective concrete mixes only in that they contained no coarse aggregate, i.e. for a particular mortar mix the ratio of water to cement, and fine aggregate to cement, was exactly the same as for the corresponding concrete mix.

TABLE II.7

Mix Proportions (by Weight)

	Mix Name	Water	Cement	Coarse Agg.	Fine Agg.
CONCRETE	BCY	0,50	1	3,28	2,08
	CCX	0,58	1	3,28	2,08
	CCY	0,58	1	3,90	2,42
MORTAR	BMY	0,50	1	-	2,08
	CMX	0,58	1	-	2,08
	CMY	0,58	1	-	2,42

From Table II.7 it is apparent that for both the concrete and mortar mixes:

(i) For a particular water/cement ratio, (0,58), two different aggregate/cement ratios were used, i.e. different volumetric concentrations of aggregate at a particular water/cement ratio; and

(ii) For a particular aggregate/cement ratio, two different water/cement ratios were used, i.e. different water contents for a particular aggregate/cement ratio.

The change in the volumetric concentration of aggregate at a particular water/cement ratio, and in the water content at a particular aggregate/cement ratio, was the maximum change possible within limits of practicability, i.e. the workability of the mix had to be considered when changing either the aggregate content or the water content of the mix.

The mix ingredients were mixed in a pan-type mixer in batches of approximately 0,055 m^3. Only one mix was made on any particular day: all the test specimens that were cast on that day were used for one series of tests. (See Section 2.2 - Test Specimens and Curing Conditions.)

The mix characteristics and average compressive strength of the respective mixes are given in Table II.8. The compressive strength is for 28 days curing at 21°C and 100 percent relative humidity. Further properties of the hardened mixes are given in PART III, CHAPTER 1.

TABLE II.8

Mix Characteristics

	MIX NAME	w/c RATIO (By Weight)	SLUMP mm	COMPACT. FACTOR	DENSITY kg/m^3	COMPRESSIVE STRENGTH AND STD. DEVIATION MPa
CONCRETE	BCY	0,50	10	0,78	2426	50,90 ± 1,60
	CCX	0,58	125	0,94	2387	38,86 ± 0,84
	CCY	0,58	10	0,80	2418	41,12 ± 1,79
MORTAR	BMY	0,50			2213	47,00 ± 0,70
	CMX	0,58			2157	39,95 ± 2,05
	CMY	0,58			2188	38,20 ± 2,30

2.2 Test Specimens and Curing Conditions

The test specimens used were 273 × 76 × 76 mm (10,75" × 3" × 3") plain concrete and mortar beams. These were cast as beams 838 mm (33") in length in specially manufactured steel moulds. From each of these beams three test specimens were subsequently cut to the required length. In casting the beams the concrete (mortar) was placed in several layers (approximately 20 mm) and compacted using a mechanical vibrator. Care was

taken to ensure full compaction; the vibration having been continued till air bubbles ceased rising to the surface of the concrete.

Specimens were covered with damp hessian sacks during the initial 24 hour hardening period. The molds were then removed and the beams placed in a humidity room (100 percent relative humidity and 21^{o}C) for 27 days. On the 27th day the beams were cut into the required lengths (273 mm) and stored in water at 30^{o}C* $\pm$ 0,2^{o}C until the heating test commenced the following day. A total of 24 test specimens were used for a series of tests at a particular temperature level.

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* This temperature was used as a datum for all temperature and expansion measurements.

CHAPTER 3 : TESTING PROCEDURES AND METHODS

3.1 Summary of Test Procedure

The investigation was performed in two phases, viz.

(i) The test specimens were allowed to dry during heating. For the duration of the heating period the thermal expansion and water loss of two respective specimens were continuously monitored. The test temperatures were 70°C, 100°C, 150°C, 250°C and 400°C respectively.

(ii) The test specimens remained fully saturated during heating and for the duration of the heating period. This was accomplished by heating the specimens under water. During heating the thermal expansion of one of the test specimens was continuously monitored. The test temperatures were 70°C and 100°C.

Apart from the abovementioned differences in test procedure, the tests performed on specimens in the two respective phases of the investigation were exactly similar.

Each test series at a particular temperature required a batch of 24 specimens. Three of these specimens were used for control tests, i.e. tested at 30°C. The remainder of the specimens were heated to the required temperature at a rate of heating of 35 deg C/hr. During heating, and for the duration of the time that the specimens were at a particular test temperature, the linear expansion of one of the test specimens was continuously monitored. For unsealed specimens the weight loss of a test specimen was monitored for the duration of the heating period.

Immediately that the desired temperature level had been attained, three of the test specimens were removed from the furnace (from the waterbath, for sealed specimens). Of these specimens, one was immediately tested in compression*. The other two test specimens were slowly cooled to the datum temperature and the residual shrinkage (or in some instances, residual expansion), moisture loss, ultrasonic pulse velocity, dynamic Young's modulus, Poisson's ratio and compressive strength determined on one of the test specimens. The other test specimen was re-immersed in water at 30°C

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* A modified compression test on the specimen.

for one week. After this period, the third test specimen was subjected to tests similar to those which had been performed on the second test specimen.

The above procedure was repeated on batches of specimens (i.e. batches of three specimens) removed at 12-hourly intervals after the time when the maximum temperature had been attained. Thirty-six hours after the maximum temperature was attained the specimens still remaining in the furnace (waterbath) were cooled to 30°C and subjected to two temperature cycles. The maximum cycling temperature was the same as the temperature during the preceding heating period. At each peak of the temperature cycle, batches of three specimens were removed and tested in a similar manner as the batches that were removed during the 48-hour heating period.

3.2 Heating Method

3.2.1 Unsealed Specimens

A total of twenty specimens were heated for every series of tests at a particular temperature. These specimens were all manufactured from one batch of concrete (mortar) and all underwent similar curing. The test specimens were heated in two electric furnaces containing respectively 2 test specimens and 18 test specimens.

(i) Furnace No. 1

In Fig. II.1 the furnace containing the two test specimens is illustrated. One of these test specimens (the lower of the two in Fig. II.1) was used to determine the linear deformation of the concrete (mortar) during heating. The specimen was simply supported at each end, the one support allowing for horizontal movement in a direction parallel to the length of the test specimen. In contact with each end of the test specimen was a fused silica rod. The silica rods were simply supported on rollers within the furnace and extended through the furnace walls. On the outside of the furnace the silica rods were connected to the spindle of a dial gauge. The other end of the dial gauge spindle was coupled to a linear variable displacement transducer*. The l.v.d.t. emitted a voltage proportional to the displacement of the dial gauge spindle, i.e. proportional to the linear deformation of the test specimen. Thus a continuous record of the linear deformation

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* Referred to as l.v.d.t. subsequently.

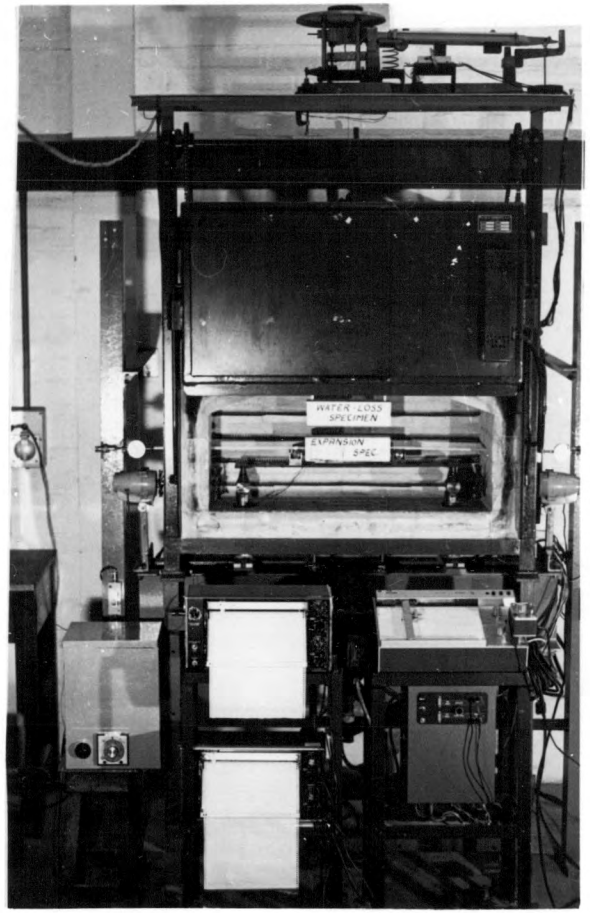

FIG. II.1 - Furnace No. 1, showing the relative positions of the test specimens, dial gauge/l.v.d.t. apparatus, and the balance for water loss measurements.

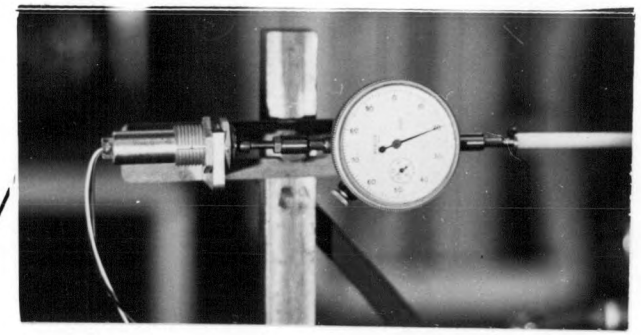

FIG. II.3 - The dial gauge/l.v.d.t. apparatus used to measure the linear deformation of a test specimen.

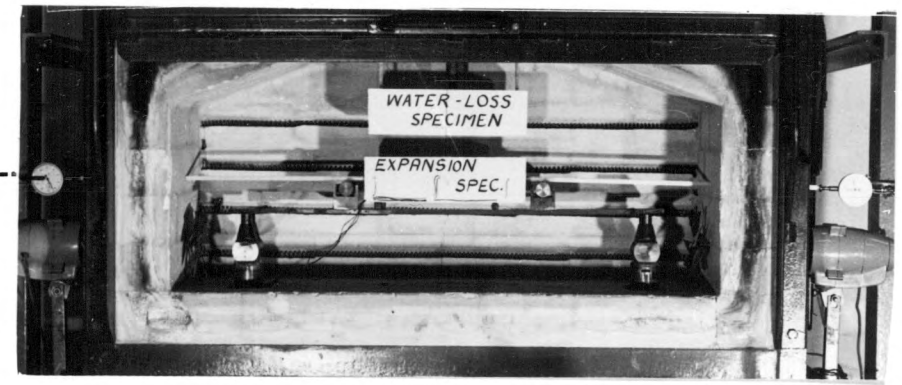

FIG. II.2 - The positions of the test specimens within Furnace No. 1.

of the test specimen could be plotted by a strip-chart recorder. The dial gauge, in addition to having been used for calibration of the l.v.d.t.'s, provided a useful check on the displacement measurements. In Fig. II.2 the position of the test specimen within the furnace, the silica rods and the dial gauge/l.v.d.t. apparatus is shown. Fig. II.3 illustrates the connection of the l.v.d.t. in series with the spindle of the dial gauge and the silica rod. More detailed descriptions of the abovementioned apparatus are given in CHAPTER 4- APPARATUS.

During heating the average temperature was measured within the test specimen used to determine the linear deformation. Two copper/constantan thermocouples were cast into the specimen. The positions of these were:

(a) at the centre of the specimen at midspan;

(b) at the centre of the specimen at a distance of 25 mm from one end.

A further two thermocouples were attached to the surface of the test specimen. These were at midspan and at a distance of 25 mm from one end of the specimen. The free ends of the four thermocouples were passed through an aperture in the wall of the furnace to a constant temperature environment* and connected in series, i.e. the output voltages of the thermocouples were summed. Consequently, a continuous record of the average temperature (in terms of millivolts) of the test specimen could be plotted by a strip-chart recorder. The thermocouples are visible on the expansion specimen in Fig. II.2.

The uppermost test specimen in Fig. II.1 and II.2 was used to determine the water loss of the concrete during heating. This specimen was freely suspended by a cable from a balance situated on top of the furnace. The position of the balance is shown in Fig. II.1. The balance was electronically adapted to give a voltage output proportional to the deflection of the balance. A continuous record of the water loss during heating of the test specimen could thus be plotted by a strip-chart recorder.

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* The temperature was always $30^{o}C \pm 0,2^{o}C$.

(ii) Furnace No. 2

Furnace No. 2 is illustrated in Fig. II.4. This furnace contained eighteen test specimens which were removed in batches of three at various times during the heating period. For a particular test series, the rate of heating and temperature level of this furnace was exactly the same as for Furnace No. 1. Furthermore, the method of measuring the average temperature within one test specimen was the same as that used to determine the average temperature of the specimen in Furnace No. 1. Further particulars regarding the apparatus are given in CHAPTER 4 - APPARATUS.

3.2.2 Sealed Specimens

A total of nineteen test specimens were heated for a series of tests at a particular temperature. These specimens were all manufactured from one batch of concrete (mortar) and all underwent similar curing. The test specimens were heated in two waterbaths containing respectively one test specimen and eighteen test specimens.

(i) Waterbath No. 1

In Fig. II.5 and Fig. II.6 the waterbath that contained one test specimen is illustrated. The specimen was used to determine the linear deformation of the concrete (mortar) during heating. This specimen was simply supported at each end, the one end allowing for horizontal movement in a direction parallel to the length of the beam.

The method of expansion measurement was the same as that used for unsealed specimens, i.e. two fused silica rods in contact with the respective ends of the specimen, passed through an aperture in the sides of the waterbath to a dial gauge/l.v.d.t. measuring system. Flexible seals made of soft rubber prevented the loss of water through the apertures. The rubber seals are visible in Fig. II.6. Further information regarding the abovementioned apparatus is given in CHAPTER 4 - APPARATUS.

The output from the two l.v.d.t.'s were connected to a strip-chart recorder. Thus the linear deformation of the test specimen for

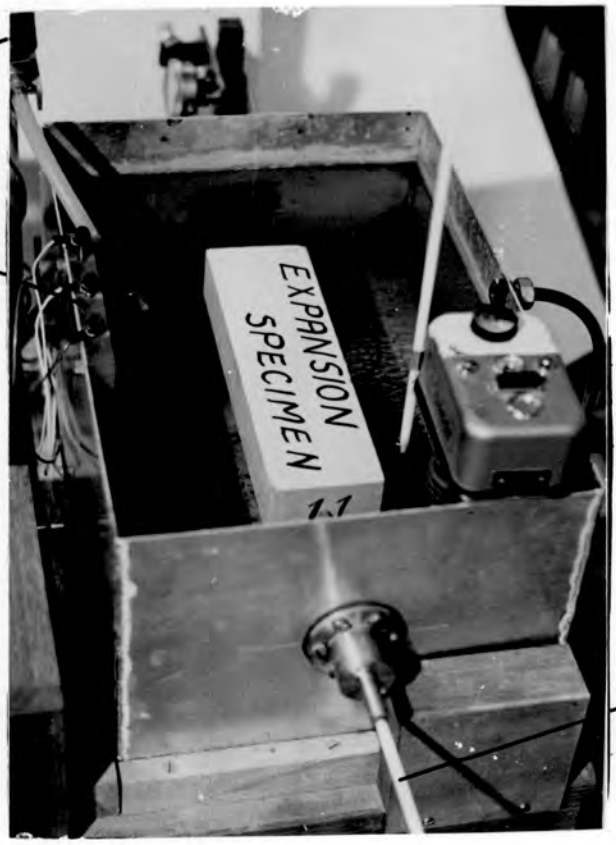

FIG. II.5 - Waterbath No. 1.

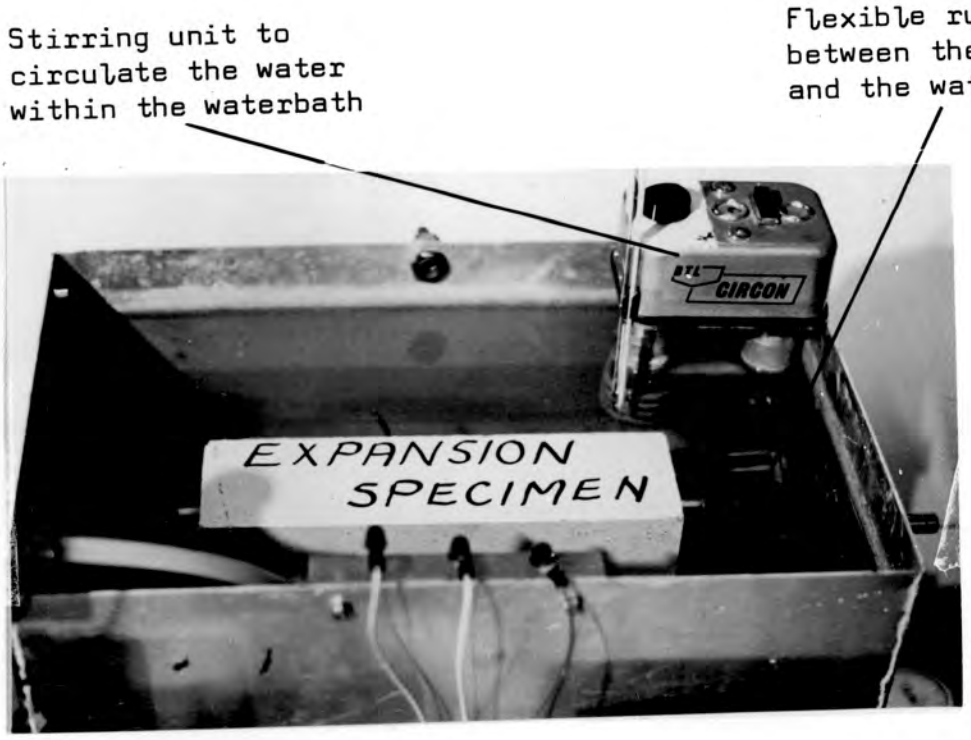

FIG. II.6 - Waterbath No. 1 containing the test specimen for determing linear deformation.

FIG. II.4 - Furnace No. 2.

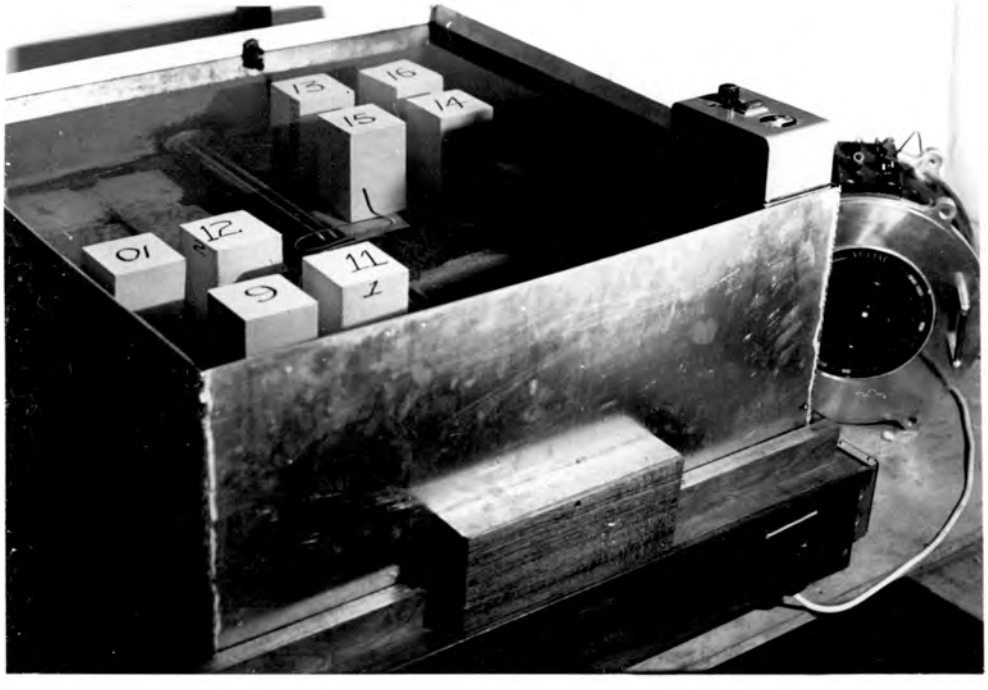

FIG. II.7 - Waterbath No. 2.

the duration of the heating period was obtained. A continuous record of the average temperature within the specimen was obtained from four copper/constantan thermocouples; two within the test specimen and two attached to the surface of the test specimen. The position of the respective thermocouples, and the method of averaging the temperatures was exactly the same as for the thermocouples which were used to measure the average temperature of unsealed specimens. [See Section 3.2.1 subsection (i)].

(ii) Waterbath No. 2

Waterbath No. 2 could accommodate eighteen test specimens; the waterbath is illustrated in Fig. II.7. The average temperature of one of the test specimens was determined in a similar manner to that in Waterbath No. 1. The test specimens were removed from Waterbath No. 2 in batches of three specimens at various stages during the heating period. For a particular test series the rate of heating and temperature level of this waterbath was exactly the same as for Waterbath No. 1.

3.3 Heating Procedure

The test specimens were placed in a pre-heating waterbath at $30^{o}C \pm 0,2^{o}C$ for the 24 hours prior to heating, i.e. the datum temperature of all expansion measurements was $30^{o}C$. Both furnaces (waterbaths) were heated to this temperature before the specimens were placed within them.

The test temperatures* for unsealed specimens were $70^{o}C$, $100^{o}C$, $150^{o}C$, $250^{o}C$ and $400^{o}C$. The test temperatures* for sealed specimens were $70^{o}C$ and $100^{o}C$. For both sealed and unsealed specimens the rate of heating was 35 deg C/hr. The total duration of a series of tests at a particular temperature was approximately 72 hours. During this time batches of three specimens were removed from Furnace No. 2 (Waterbath No. 2):

(a) immediately the average temperature had reached the desired temperature level of a particular test series;

(b) twelve hours after event (a)

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* The desired temperature level was maintained to within 1 percent by all the furnaces and waterbaths. This is discussed in CHAPTER 4 - APPARATUS.

(c) twenty-four hours after event (a); and

(d) thirty-six hours after event (a),

and subjected to tests as described in Section 3.4 - Physical Tests and Measurements. Both furnaces (waterbaths) were then cooled to the datum temperature ($30^{o}C$) at a cooling rate not exceeding 50 deg C/hr*. The temperature was maintained at $30^{o}C$ for approximately two hours, whereupon both furnaces (waterbaths) were re-heated to the test temperature level. The rate of heating was 35 deg C/hr. Two hours after the desired test temperature was attained, a batch of three specimens was removed from Furnace No. 2 (Waterbath No. 2). Another batch of three specimens was removed after a further cooling and heating cycle. The batches of specimens which were removed during the respective heating cycles were subject to tests as described in Section 3.4 - Physical Tests and Measurements.

The two test specimens in Furnace No. 1 (one test specimen in Waterbath No. 1) were cooled to the datum temperature ($30^{o}C$). For the duration of the heating period, the respective specimens in Furnace No. 1 provided continuous measurement of:

(a) linear deformation and average temperature

(b) water loss.

The test specimen in Waterbath No. 1 enabled continuous measurement of the linear deformation and average temperature during heating. These measurements were plotted by strip-chart recorders.

3.4 Physical Tests and Measurements

The physical tests which were performed during the two phases of this investigation, viz. (i) the specimens were allowed to dry during heating, and (ii) the specimens remained fully saturated during heating, were exactly the same. The tests on sealed and unsealed specimens are therefore discussed simultaneously. However, this should not be misconstrued as meaning that the tests on sealed and unsealed specimens were performed concurrently.

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* For unsealed specimens this was done by lagging the specimen with asbestos wool within an oven. The temperature control of the oven was set to $30^{o}C$ and the specimens allowed to cool. The sealed specimens were placed in a small waterbath containing water at the same temperature as that of the test specimens. The waterbath temperature control was set to $30^{o}C$ and the water allowed to cool (see CHAPTER 4 - APPARATUS).

3.4.1 Reference Tests and Measurements

All the test specimens were kept in a waterbath at $30^{o}C \pm 0,2^{o}C$ for 24 hours prior to heating. Before placing the test specimens in the respective furnaces (waterbaths), the following were determined for all specimens:

(i) The length, correct to $2,5 \times 10^{-4}$ mm. The length measurement was obtained using the apparatus* shown in Fig. II.8.

(ii) The mass, correct to 1 g.

(iii) The ultrasonic pulse velocity*.

(iv) Dynamic Young's modulus*. (The method of calculation is given in APPENDIX I.1).

(v) Poisson's ratio. Poisson's ratio was calculated from measurements (i) to (iv) above. (The method of calculation is given in APPENDIX I.2).

After the above tests had been performed, three of the test specimens were tested in compression using a modified compression test. The modified compression test enabled two compressive strength measurements per specimen, i.e. six compression tests were performed on unheated specimens at $30^{o}C$.

3.4.2 Physical Tests and Measurements during Heating and after Cooling from the Test Temperature

All the respective batches of three test specimens that were removed from Furnace No. 2 (Waterbath No. 2) during heating and during temperature cycling were tested in a similar manner. The test procedure was:

(a) The mass of each specimen was determined (whilst hot)

(b) The compressive strength of one of the test specimens was determined whilst hot. (Two modified compression tests.)

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* A description of the apparatus, and method of use, is given in CHAPTER 4 - APPARATUS.

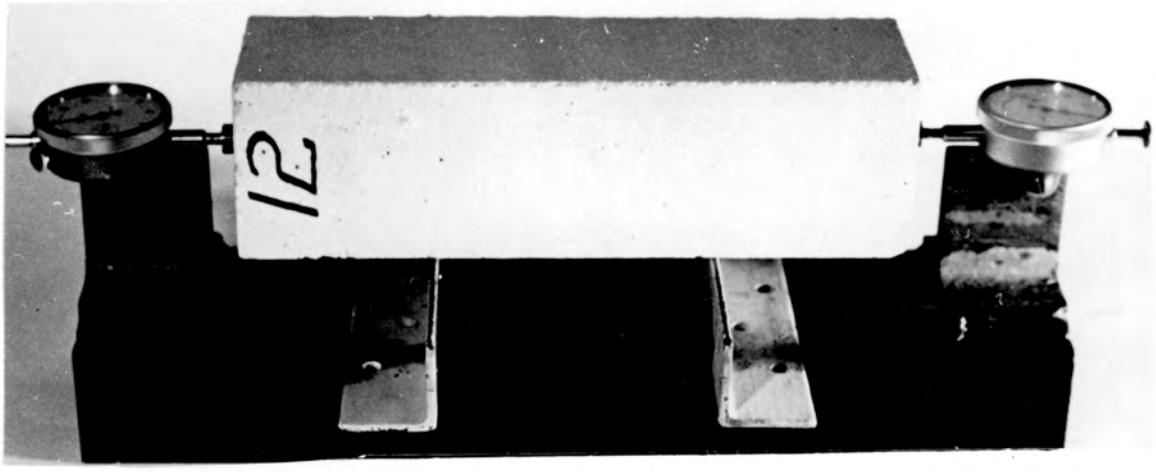


FIG. II.8 - The apparatus used to measure the length of test specimens before heating and after cooling from temperature.

(b) The other two test specimens were cooled to $30^{o}C$ at a cooling rate not exceeding 50 deg C/hr. Within four hours after the specimens had cooled to $30^{o}C$, the following were determined on one of the two specimens:

(i) The length, correct to $2{,}5 \times 10^{-4}$ mm.

(ii) The mass, correct to 1 g.

(iii) The ultrasonic pulse velocity.

(iv) Dynamic Young's modulus.

(v) Poisson's ratio (calculated).

(vi) The compressive strength.

The second of the two specimens which had been cooled to $30^{o}C$ was re-immersed in water at $30^{o}C$ for a period of one week. Measurements (i) to (vi) were then carried out on this specimen.

CHAPTER 4 : APPARATUS

4.1 Heating Apparatus

4.1.1 Unsealed Specimens

(i) Furnace No. 1

Furnace No. 1 was adapted so that a continuous record of the linear deformation and water loss of two respective specimens could be obtained for the duration of the heating period. The position of these test specimens within the furnace is illustrated in Fig. II.9. Shown also in Fig. II.9 is the apparatus for temperature control of the furnace; linear expansion measurement of a test specimen; the measurement of water loss of a test specimen; and the recorders which continuously monitored expansion, water loss and specimen average temperature. The respective subsections in which this apparatus is discussed, are indicated in Fig. II.9.

Furnace No. 1 operated off a 220 V - 230 V single-phase power supply and had a maximum power consumption of 4500 watts. The heating rate within the furnace was controlled by a variable transformer; the maximum heating rate was 120 deg C/hr and the minimum heating rate 35 deg C/hr.

The temperature within the furnace was controlled by a temperature controller (0 to 500^{o}C) which monitored the furnace temperature by means of an iron/constantan thermocouple within the furnace. This system controlled the temperature to within 1 percent of the desired value. A single-channel chart recorder (operating off a second iron/constantan thermocouple within the furnace) provided a continuous record of the furnace temperature. In Fig. II.10 a circuit diagram of the furnace control instrumentation is illustrated.

In preliminary tests it was found that the temperature difference between the top and bottom of the furnace was 15 deg C when the furnace temperature was 400^{o}C. Consequently, two fans were built into the furnace: the positions of the fans are illustrated in

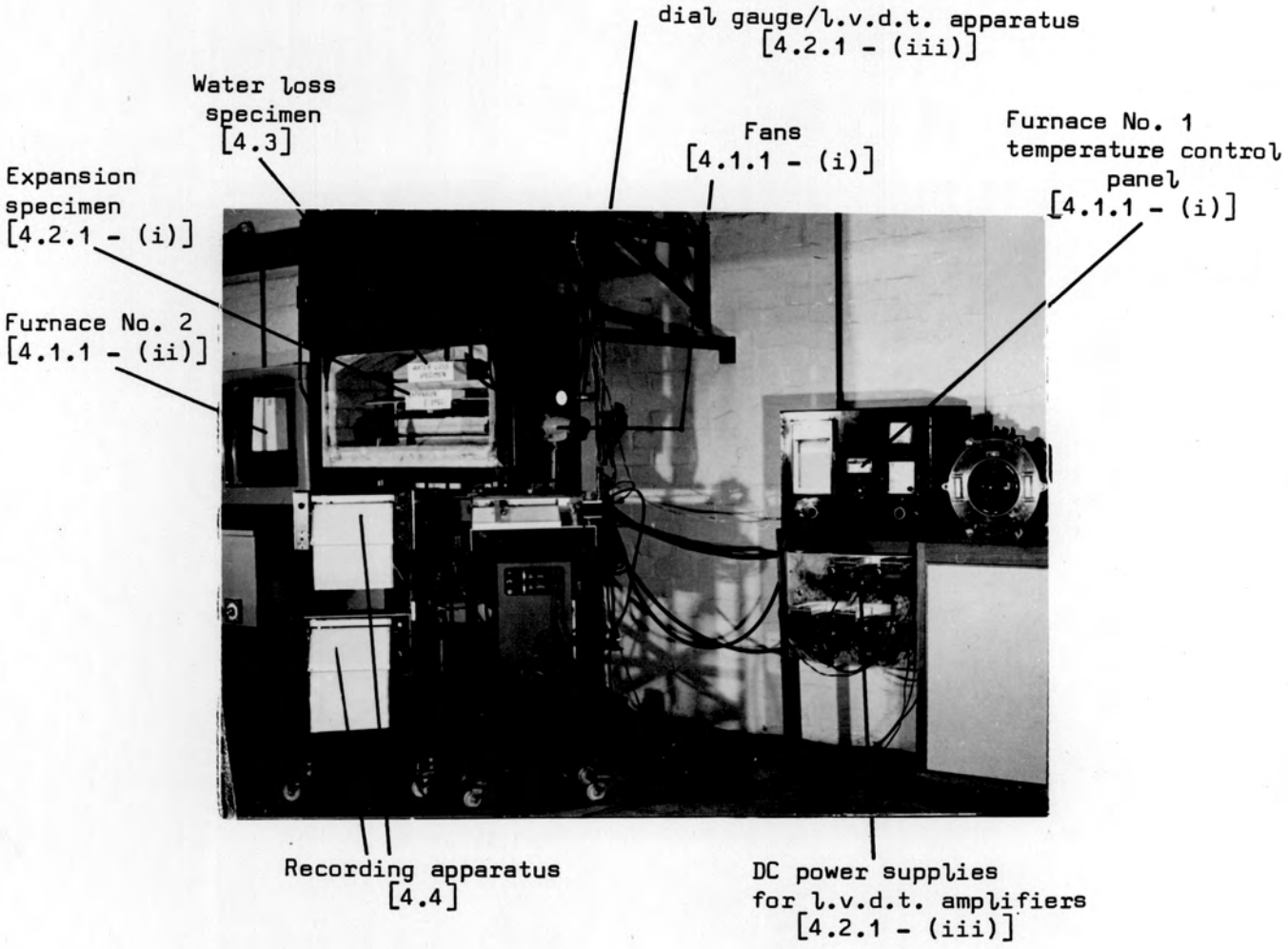


FIG. II.9 - Furnace No. 1 and ancilliary equipment.

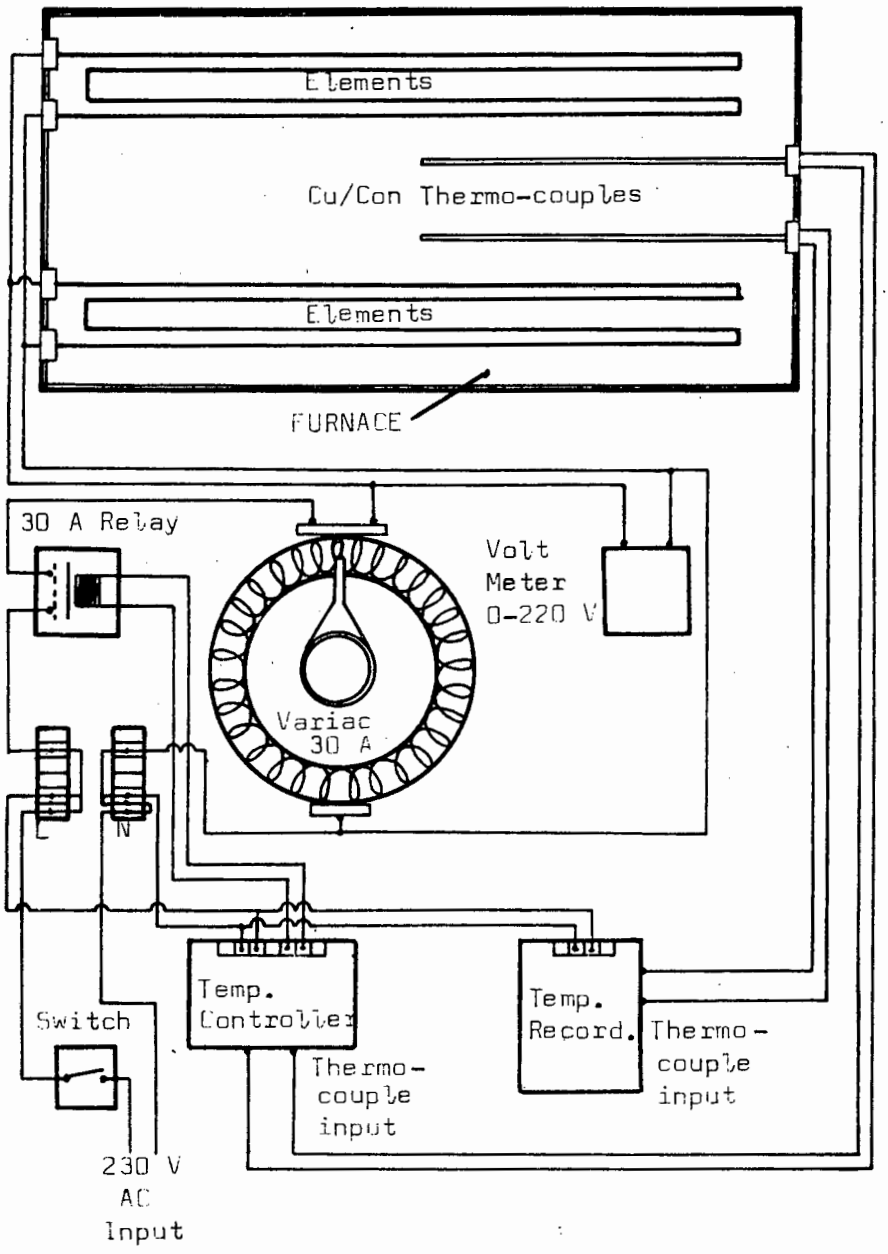


FIG.II.10: The circuitry of the furnace temperature control instrumentation.

in Fig. II.9. These fans improved the temperature distribution throughout the furnace. At no point within the furnace did the temperature differ from the desired temperature by more than 1 percent of the desired temperature level.

(ii) Furnace No. 2

Furnace No. 2 contained 18 test specimens which were removed in batches of three specimens at various times during the heating period. The furnace operated off a 220 V - 230 V single-phase power supply and had a maximum power consumption of 6600 watts. The heating rate within the furnace was controlled by a variable transformer; the maximum heating rate was 65 deg C/hr and the minimum heating rate 15 deg C/hr. (These values are for the furnace loaded with the eighteen test specimens.) The temperature control and the circuitry of this furnace were basically the same as for Furnace No. 1, with the exception that Furnace No. 2 did not have a chart recorder for monitoring furnace temperatures.

A large fan built into one of the walls of the furnace, ensured that the temperature difference between the top and bottom of test specimens within the furnace was small. In preliminary tests it was found that the maximum temperature difference between the top and bottom of a test specimen was not greater than 1 percent of the particular temperature level. These tests also indicated that the furnace temperature was controlled to within 1 percent of the desired temperature level.

(iii) Pre-Heating Waterbath

The pre-heating waterbath was used to store all the test specimens at $30^{o}C$ for the 24 hours preceding the heating test. The waterbath was made of galvanized iron and had dimensions of 750 × 750 × 300 mm. Water temperature within the bath was controlled to $30^{o}C \pm 0,2$ deg C by a 'Haake : Type E52' contact thermometer and heater. The heating apparatus incorporates facilities for circulating the water within the bath.

The waterbath was cleaned and filled with fresh water for each successive bath of 24 test specimens that were placed within it, i.e. twice weekly.

(iv) Cooling Oven

The cooling oven was used to cool two of each successive batch of three specimens that were removed from Furnace No. 2 at various times during the heating period. The inner dimensions of the oven were 400 × 400 × 400 mm and the construction was of 6 mm asbestos sheeting. No further insulation was necessary as the test specimens to be cooled were lagged with asbestos wool before they were placed within the oven.

The oven temperature control was by means of a chrome/alumel thermocouple within the oven, coupled to a temperature controller set to 30°C. The temperature controller switched two 250 watt heating elements within the oven.

In preliminary tests it was found that the cooling rate of test specimens initially at 400°C, was less than 50 deg C/hr. For specimens initially at 100°C the cooling rate was approximately 30 deg C/hr. When the specimens had cooled to 30°C, the temperature controller maintained a constant temperature of 30°C ± 0,5 deg C within the oven.

(v) Post-Cooling Waterbath

The post-cooling waterbath was used to store one of the test specimens (from each successive batch of three specimens) that was removed from Furnace No. 2 at various times during the heating period. The specimen was cooled to 30°C [as in (iv) above] before it was re-immersed in water for seven days. The temperature within the waterbath was maintained at 30°C ± 0,2 deg C, the heating method and description of the apparatus being the same as that for the pre-heating waterbath. This is discussed in subsection (iii) of this Section.

4.1.2 Sealed Specimens

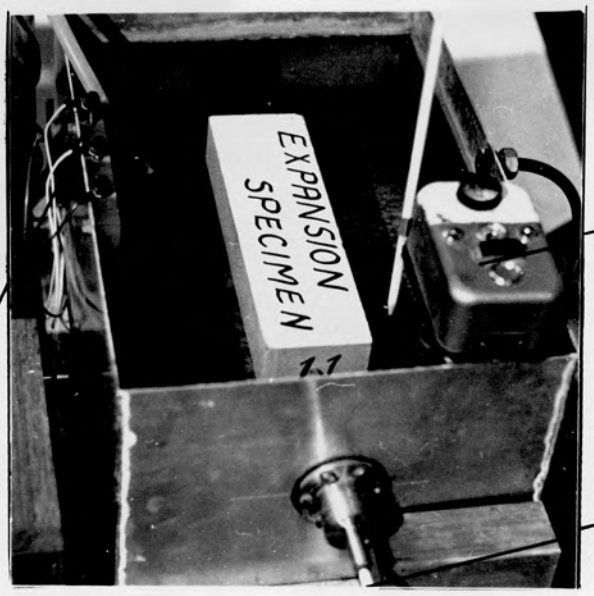
(i) Waterbath No. 1

Waterbath No. 1 contained one test specimen only. The waterbath was designed so that the linear deformation of the test specimen could be obtained continuously for the duration of the heating period. The position of the test specimen within the waterbath is shown in Fig. II.11. In Fig. II.12 the apparatus for temperature control of the waterbath; water level control of the waterbath; measurement of linear expansion of the test specimen; and the recorders which continuously monitored the specimen expansion and average temperature, is shown. The respective subsections in which this equipment is discussed, are shown on Figs. II.11 and II.12.

Waterbath No. 1 was made of galvanized iron and had dimensions of 450 × 300 × 225 mm. The waterbath operated off a 220 V - 230 V single-phase power supply and had a maximum power consumption of 3000 watts. The rate of heating within the waterbath was controlled by a 0 - 230 V variable transformer: the maximum heating rate was 50 deg C/hr and the minimum heating rate 20 deg C/hr.

The water temperature was controlled by a temperature controller coupled to a chrome/alumel thermocouple within the waterbath. This system controlled the temperature to within 1 percent of the desired value, the maximum temperature attainable having been 100^{o}C.

Despite the fact that the waterbath was closed with a lid to minimize water loss by evaporation during heating, water had to be added at frequent intervals during the heating period. The water level was controlled by a 'floatless switch' which sensed the level of the water in the waterbath by means of two probes. The depths of the two probes within the waterbath differed by 1 mm; the upper probe being at the desired water level. When the water level had fallen by more than 1 mm, the change in water level was sensed by the switching mechanism. The switching mechanism activated a solenoid tap on a water-supply feedline to the waterbath, and allowed the flow of water into the waterbath. The flow of water was stopped by the solenoid/switching mechanism when the water level had risen to the level of the upper probe.

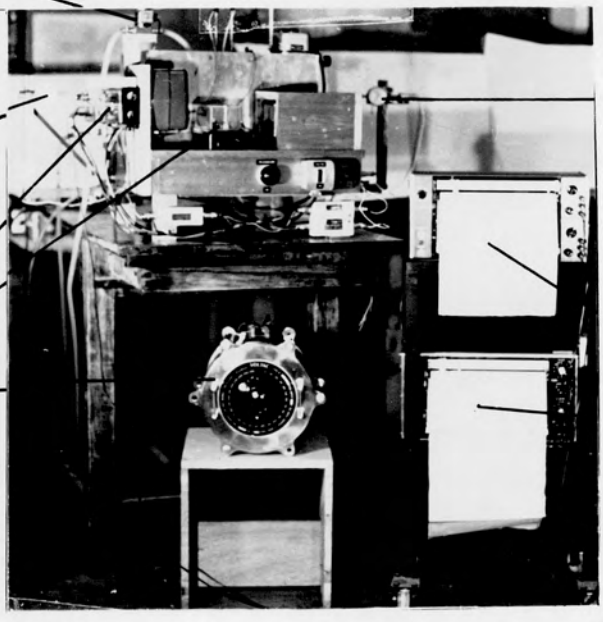


Water circulating pump [4.1.2 - (i)]

Silica rod [4.2.1 - (iv)]

FIG. II.11 - Position of the test specimen within Waterbath No. 1.

Water level control equipment [4.1.2 - (i)]



Dial gauge/l.v.d.t. apparatus [4.2.1 - (iv)]

Dial gauge/l.v.d.t. apparatus [4.2.1 - (iii)]

Equipment for Temperature control [4.1.2 - (i)]

Recording apparatus [4.4]

FIG. II.12 - Waterbath No. 1 and ancilliary equipment.

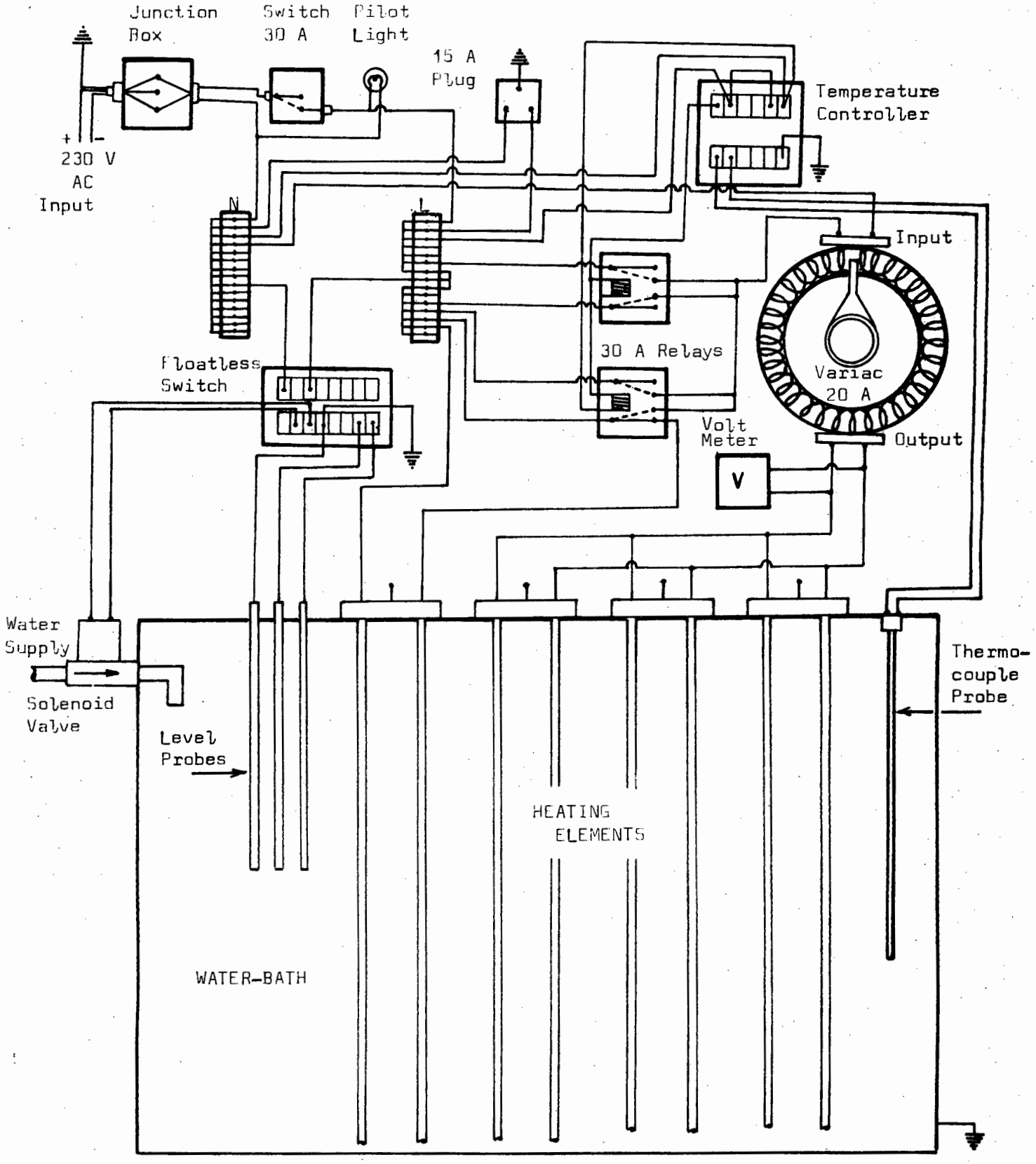


FIG.II.13: The circuitry of Waterbath No.1 and Waterbath No.2 temperature control and water level control apparatus.

A water circulating pump ensured that the added water was evenly distributed throughout the waterbath, thus minimizing temperature fluctuations. A series of preliminary tests indicated that the water temperature within the waterbath was temporarily decreased by approximately 3 deg C whenever the water level adjustment occurred. However, the average temperature of the test specimen fluctuated by less than 1 deg C.

A circuit diagram of the temperature control and water level control equipment of Waterbath No. 1 is given in Fig. II.13.

The waterbath was cleaned twice weekly and refilled with fresh water, i.e. for every new series of tests.

(ii) Waterbath No. 2

Waterbath No. 2 contained 18 test specimens which were removed in batches of three specimens at various times during the heating period. The waterbath was made of galvanized iron and had dimensions of 900 × 900 × 350 mm. The power consumption was 6600 watts at 200 V; this voltage resulting in a heating rate of 55 deg C/hr. A 30 A variable transformer could reduce the heating rate to a minimum value of 20 deg C/hr.

Apart from the abovementioned differences between Waterbath No. 2 and Waterbath No. 1, the basic circuitry and instrumentation for temperature control and water level control of Waterbath No. 2 were similar to that of Waterbath No. 1 (see Fig. II.13). However, the fluctuations in temperature within Waterbath No. 2 were greater than those in Waterbath No. 1. This was because a relatively large volume of water was added whenever a batch of three test specimens was removed from the waterbath. Preliminary tests indicated that the average temperature of test specimens within the waterbath was temporarily reduced by as much as 3 deg C when a batch of three specimens was removed from the waterbath. However, the correct temperature level was again attained within approximately ten minutes.

The waterbath was cleaned twice weekly and refilled with fresh water, i.e. for every new series of tests.

(iii) Pre-Heating Waterbath

The pre-heating waterbath was used to store all the test specimens at 30°C for the 24 hours preceding the heating test. The waterbath that was used for the pre-heating of sealed specimens was the same as that used for pre-heating unsealed specimens; described in Section 4.1.1, subsection (iii).

(iv) Cooling Waterbath

The cooling waterbath was used to cool two specimens of each successive batch of three specimens that were removed from Waterbath No. 2 at various times during the heating period. The cooling waterbath consisted of a 375 × 225 × 125 mm stainless steel container wherein the water temperature was controlled by a 'Haake : Type E52' contact thermometer and heater.

The initial temperature in the waterbath was the same as the temperature of the test specimens that were to be cooled. The test specimens were immersed in the waterbath and the waterbath temperature control set to 30°C. The cooling rate of the test specimens cooled in this manner was not greater than 30 deg C/hr. When the temperature had fallen to 30°C, the temperature control and heater maintained this temperature to within 0,2 deg C.

The waterbath was cleaned twice weekly and re-filled with fresh water.

(v) Post-Cooling Waterbath

The post-cooling waterbath was used to store one of the test specimens from each successive batch of three specimens that were removed from Waterbath No. 2 at various times during the heating period. The test specimen was cooled to 30°C [as under (iv) above] before it was placed in the post-cooling waterbath. Test specimens were kept for 7 days at 30°C ± 0,2 deg C. The waterbath used was the same as that used for unsealed specimens; described in Section 4.1.1, subsection (i).

4.2 Apparatus for Measuring the Linear Deformation of Test Specimens

4.2.1 Linear Deformation during Heating

(i) General Description

During the heating period the linear deformation of unsealed and sealed specimens was determined in Furnace No. 1 and Waterbath No. 1 respectively. In each case the test specimen was simply supported at each end, the one support allowing for horizontal movement of the specimen in a direction parallel to the length of the test specimen. In contact with each end of the test specimen was a silica rod. The silica rods were simply supported on rollers within the furnace (waterbath) and extended through the furnace (waterbath) wall on either side of the test specimen. On the outside of the furnace (waterbath) each silica rod was connected to the spindle of a dial gauge mounted on a vertical steel column. On the side opposite to that where the silica rod was attached, the spindle of the dial gauge was coupled to a linear variable displacement transducer*. The transducer gave an output voltage proportional to the displacement of the dial gauge spindle, i.e. proportional to the displacement of the test specimen. This enabled a continuous record of the linear deformation of a test specimen to be plotted by a strip chart recorder. In Fig. II.14 and Fig. II.15 the measuring system as used in Furnace No. 1 is illustrated. With one exception, the measuring system used in Waterbath No. 1 was exactly similar to that used in Furnace No. 1. The exception was that the apertures for the silica rods to pass through the sides of the waterbath were sealed to prevent the loss of water. This was achieved by having a flexible rubber seal between the silica rod and the circumference of the aperture. The rubber seal is shown in Fig. II.6.

The output voltages of the two l.v.d.t's (i.e. one at each end of a test specimen) were summed by having the output leads connected in series. Thus the recorder plotted the total linear deformation as a single line on the graph paper.

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* l.v.d.t.

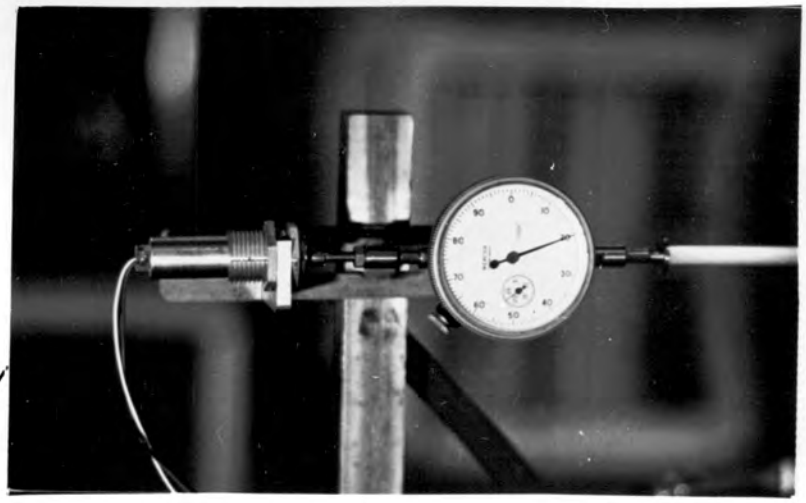


FIG. II.15 - The dial gauge/l.v.d.t. apparatus for monitoring linear deformation of a test specimen.

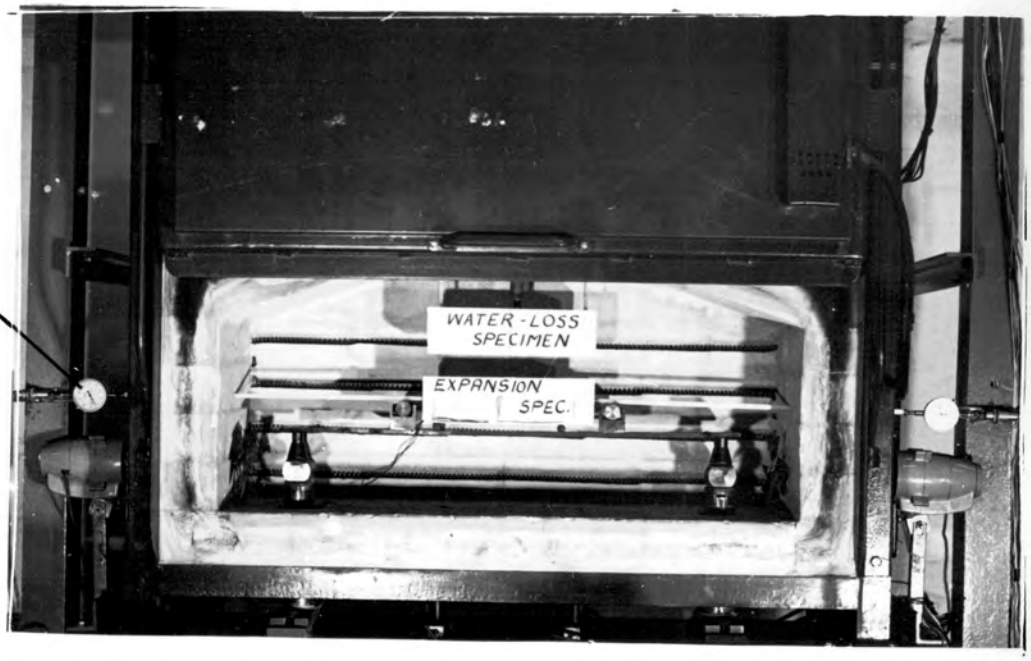


FIG. II.14 - The system to measure linear deformation of a test specimen during heating.

(ii) Compensation for Movement of the Supporting Columns

The linear deformation of the test specimen had to be corrected for a change in distance between the columns supporting the dial gauge/l.v.d.t. equipment. This was because the support columns were interconnected and therefore affected by changes in ambient temperature. Although the correction that had to be applied was very small, it was nevertheless significant.

Since the support columns did not move apart in a parallel manner, the change in distance between the columns had to be measured at the height at which the dial gauge/l.v.d.t. equipment was attached (say level A). This was not possible. Consequently, the change in distance between the columns was measured at some distance below the dial gauge/l.v.d.t. equipment (say level B). This was done by having a silica rod in contact with one column and coupled to a dial gauge/l.v.d.t. on the other column. Prior to the start of the testing programme the ratio of the distance change at level B to that at level A was determined by experiment. Using this ratio, the amplification of the l.v.d.t. at level B was adjusted so that the output voltage corresponded to that voltage which would have occurred if the l.v.d.t. was positioned at level A. This voltage was connected in series with the voltages from the two l.v.d.t.'s measuring linear deformation of the test specimen. Consequently, only the voltage representing the true linear deformation of a test specimen was plotted by the strip-chart recorder. The calibration of the linear deformation measuring apparatus was checked as described in APPENDIX I.3.

(iii) Dial Gauge/l.v.d.t. Apparatus

The dial guage/l.v.d.t. arrangement that was used in this investigation is illustrated in Fig. II.15. The dial gauge could be read to $2{,}5 \times 10^{-4}$ mm and provided a useful check on the calibration of the l.v.d.t.; for every test series, dial gauge readings were taken at various intervals during the heating period.

The l.v.d.t. (linear variable displacement transducer: 'Philips : Type 9314/01') was used in conjunction with a carrier wave oscillator-demodulator ('Philips : Type PR 930(') and a 12 V DC supply. The 12 V DC supply is stabilized within the converter and

fed to a 5,6 kHz oscillator, amplifier and demodulator respectively. The oscillator output is connected to a Wheatstone bridge, part of which is formed by the l.v.d.t. When imbalance of the Wheatstone bridge occurs due to a transducer displacement, the output of the Wheatstone bridge is fed through an amplifier to the demodulator. The amplified output is demodulated by the 5,6 kHz carrier frequency and passed to the recording apparatus.

The displacement transducers had a maximum linear measuring length of 1 mm. The linear voltage output of the oscillator-demodulator could be adjusted to between 0 and 6 DC; the sensitivity of the output voltage as a function of time and as a function of ambient temperature respectively, was 0,05 percent/day and 0,04 percent/deg C. The zero point drift was 0,02 percent/day and 0,002 percent/deg C with respect to the output voltage.

The output from the oscillator-demodulator was fed to a strip-chart recorder (see Section 4.4 - Recording Apparatus). In a series of preliminary tests, the amplification of the l.v.d.t./oscillator-demodulator was adjusted so that a transducer displacement of 2×10^{-4} mm could be read as a single division on the recorder chart. This was done by adjusting the output voltage of the oscillator-demodulator to 5 V at a transducer displacement of 1 mm. The output voltage was connected to the 250 mV input of the recorder, the recorder chart having a total of 250 divisions. Consequently, the displacement of the transducer corresponding to one division on the recorder chart is equal to:

$$\frac{250}{5000} \times \frac{1}{250} \frac{\text{mV}}{(\text{mV/mm})\ \text{division}} = 2 \times 10^{-4}\ \text{mm/division}$$

The only disadvantage of the measuring and recording system was that for a large transducer displacement the recorder pen moved off the scale. However, the recorder had a 'zero offset' facility; by adjusting the 'zero offset' the pen could be returned to the original starting position on the scale.

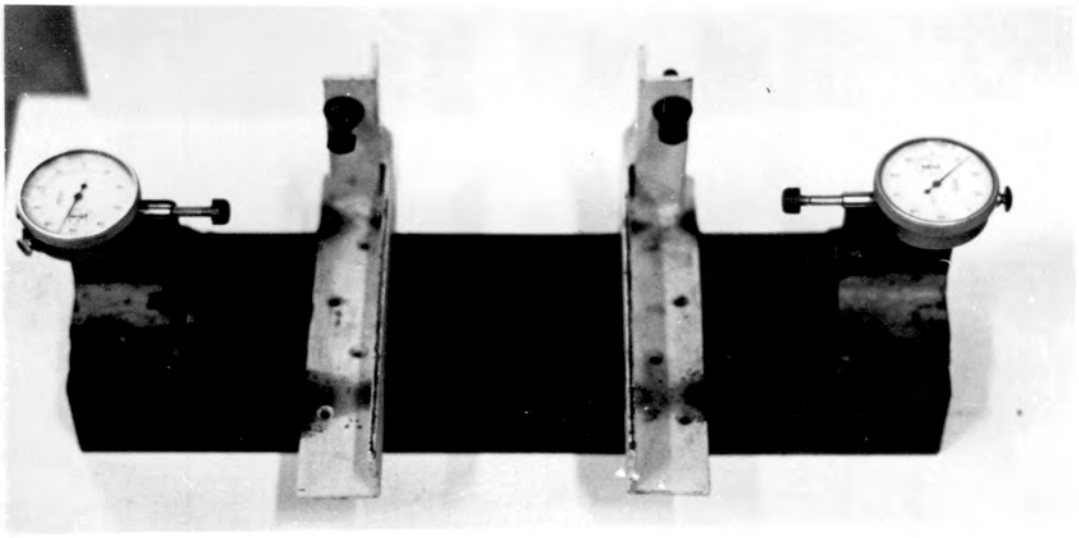
(iv) Silica Rods

Fused quartz rods (Trade name - 'Vitreosil') were used to couple the spindle of each dial gauge to the test specimen within Furnace No. 1 (Waterbath No. 1). 'Vitreosil' consists of pure silica, fused in a homogeneous uniform product containing approximately 99,6 percent SiO_2. The principal properties of this material are its resistance to chemical attack, low thermal expansion and low thermal conductivity. 'Vitreosil' has a linear coefficient of thermal expansion of $0,55 \times 10^{-6}$/deg C up to a temperature of $400^{o}C$. Consequently, the expansion of the silica rods, although small, nevertheless had to be taken into account when determining the test specimen expansion. APPENDIX I.5.1 gives the method of calculating the silica rod extension at the various test temperatures.

4.2.2 Length Measurements before Heating and after Cooling

The apparatus used to measure the length of test specimens both before heating and after cooling is shown in Fig. II.16. In successive length measurements of a particular specimen, the specimen was always situated in the same position in relation to the two dial guages. This was achieved by placing the specimen into the apparatus always with (i) the same face upwards; (ii) the same face bearing against two smooth stops behind the specimen; (iii) the same end towards a particular dial gauge. Before reading the dial gauges, the specimen was moved lengthwise until the dial gauge on the left showed a reading of exactly 1 mm. The reading on the gauge on the right was taken and the readings from the two dial gauges summed.

The apparatus was kept in a constant temperature room ($20^{o}C$) and gave excellent reproducibility of results, viz. ten successive readings of the dial gauges for a particular specimen, the specimen having been completely removed from the apparatus and then replaced for the successive readings, agreed to within 4×10^{-4} mm. It was not necessary to accurately calibrate this apparatus as only the relative dial gauge readings, i.e. before heating and after cooling were or importance. Consequently, the distance between the dial gauge bearing surfaces was determined to only 0,05 mm. This distance was 269,15 mm. The length of test specimens could be obtained by adding 269,15 mm to the summed dial gauge readings.



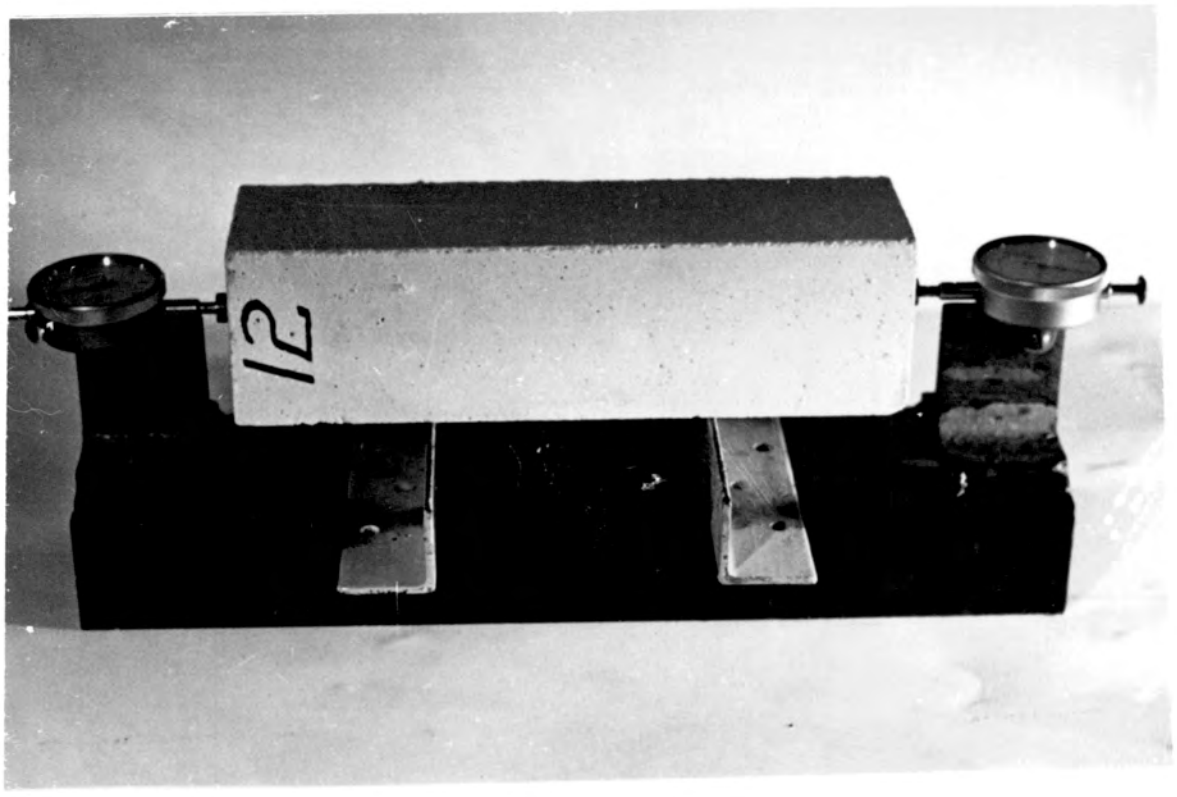


FIG. II.16 - The apparatus for measuring the length of a test specimen.

4.3 Apparatus for Measuring Water Loss During Heating

The apparatus to measure the water loss of a test specimen during heating is illustrated in Fig. II.17. The balance was situated above Furnace No. 1; the test specimen within the furnace having been suspended from the balance by means of a cable attached to the specimen at midspan. The respective positions of the balance and test specimens are illustrated in Fig. II.1.

The balance was adapted so that the water loss could be continuously monitored by a recorder. This was done by electronically measuring the displacement of a part of the balance that moved in a vertical direction as the loss of water occurred. The displacement was measured by a l.v.d.t.; the specifications of the l.v.d.t. are similar to those described in Section 4.2.1 - subsection (iii). In Fig. II.17, the position of the l.v.d.t. on the balance is shown. The maximum linear measuring length of the l.v.d.t. was 5 mm. Consequently, the vertical displacement of the point to which the l.v.d.t. sensor was attached had to be less than 5 mm for the maximum anticipated water loss (approximately 500 g). This was achieved by damping the movement of the balance beam with a spring. The position of the spring and the spring constant was determined by trial and error.

The water loss apparatus was calibrated in such a manner that one division on the chart paper represented a water loss of 1 g. This was done by adjusting the output of the l.v.d.t. to 4 V for the displacement of the transducer which corresponded to a water loss of 500 g. Connected to the 2 V input of a recorder with chart paper sub-divided into 250 division, the water loss corresponding to one division is equal to:

$$\frac{2}{1} \times \frac{500}{4} \times \frac{1}{250} \frac{V}{V/g \;.\; \text{divisions}} = 1 \text{ g/division}$$

In some instances where large water losses occurred the recorder pen moved off the scale. However, the 'zero offset' facility of the recorder enabled the pen to be returned to the original starting position on the recorder scale.

4.4 Recording Apparatus

The recording apparatus was used to obtain continuous records of linear deformation, water loss and average specimen temperature during the heating

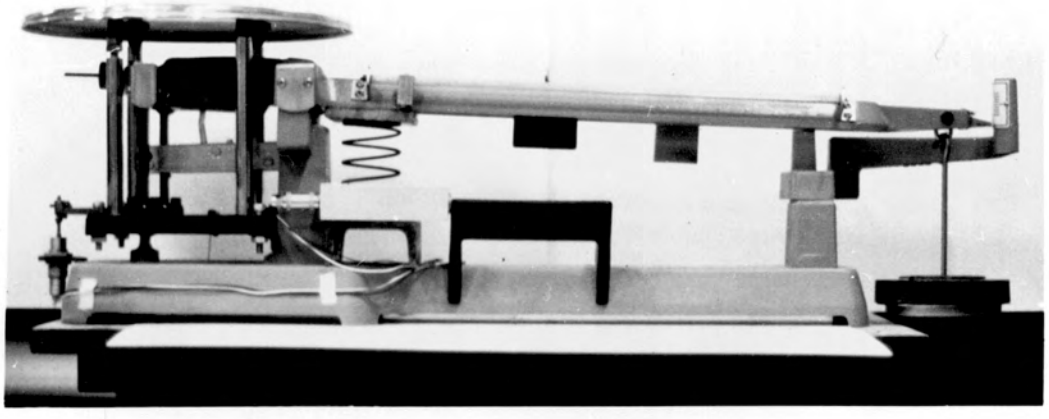


FIG. II.17 - The position of the l.v.d.t. on the balance for water loss measurement during heating.

period. Two similar 'Hewlett-Packard' recorders were used in this investigation. Each recorder conststs of a two-pen strip-chart recorder with independent pen drives. The pens are each activated by a multi-span input module, ('Hewlett-Packard' 17501-A multi-span plug-in types) with an input impedance of 1 M Ω and continuously variable span control. Sixteen calibrated spans from 1 mV to 100 V full scale are available. For every span, the zero can be offset by up to five times the full scale deflection. The accuracy of the input module is ± 0,2 percent full scale and the module has a linearity of ± 0,1 percent full scale. The operating power for the module is derived from the strip-chart recorder which operates off 220 V - 230 V mains. The chart transport system has twelve selectable speeds ranging from 25 mm/hour to 50 mm/second. Standard chart rolls with a 250 mm writing width were used.

4.5 Physical Test Apparatus

4.5.1 Compression Testing Equipment

The compression test specimens were tested on an 'Amsler' 3000 kN compression tester. The apparatus has three scale ranges at which testing can be performed, viz. 600 kN, 1500 kN and 3000 kN respectively. The 1500 kN range was the one mostly used for the compression tests in this investigation. A 'Hydro-Pacer' installation enabled the load to be applied at a constant rate, a wide range of loading rates having been available. All compression tests during the course of this investigation were performed at a rate of loading of 120 kN/min.

4.5.2 Ultrasonic Pulse Velocity

In the ultrasonic method of test, the elastic properties of the material are determined from the velocity of propagation of a pulse of waves at an ultrasonic frequency. Pulse velocity determinations were made using an ultrasonic materials tester. ('Emefco - Type UCT 3'). The instrument has two transducers of frequency 100 kc/s. The accuracy of measurments with this equipment is given as ± 1 percent or ± 0,2 micro-seconds, whichever is the greater.

4.5.3 Dynamic Young's Modulus

The dynamic Young's modulus was obtained by the determination of the fundamental longitudinal resonant frequency of the beam specimens. The apparatus consists of an electro-dynamic materials tester ('Emefco : Type SCT 5') and a standard test-bench. The SCT 5 consists of an accurately calibrated oscillator coupled to a vibrator for excitation of the specimen. The vibrator is in contact with one end of the beam specimen. An amplifier feeds a meter which measures the signal from a crystal pick-up in contact with the other end of the specimen.

A standard test-bench which complies with the requirements of the British Standard for Testing Concrete (B.S. 1881, 1970) was used. The test specimens are supported at midspan and the vibrator and crystal pick-up are brought into contact with the two ends of the specimen respectively. The vibrator supplies small amplitude vibrations which set up standing waves in the beam specimen. By varying the frequency of the standing waves, resonance can be established. At resonance, the lateral stresses within the beam specimen disappear and the beam behaves as a narrow rod. Elastic theory gives the following relationship between the velocity of propagation of the standing wave and the wavelength of a rod of length, L:

$$V = 2nL \propto \sqrt{\frac{E_d}{\rho}}$$

where V = velocity of the standing wave

E_d = dynamic Young's modulus

n = fundamental longitudinal resonant frequency

L = length of rod

ρ = mass density of the concrete

Hence, the dynamic Young's modulus

$$E_d = 4Kn^2 L^2 \rho$$

where K = a constant depending on the units of measurement.

PART III

EXPERIMENTAL RESULTS

INTRODUCTION

The experimental results of the tests performed on the various concrete and mortar mixes having mix proportions as illustrated in Table III.1, are given in APPENDIX II, APPENDIX III and APPENDIX IV. The data in APPENDIX II, Table A.II.1 to Table A.II.42, are for the residual linear deformation after cooling, compressive strength, water loss, ultrasonic pulse velocity, dynamic Young's modulus and Poisson's ratio of test specimens. These tests were performed on specimens which were removed from the furnace (waterbath) at various times during the heating period. The data presented graphically in APPENDIX III, Figure A.III.1 to Figure A.III.12, and APPENDIX IV, Figure A.IV.1 to Figure A.IV.42, are for the water loss and linear deformation respectively, each monitored continuously on a test specimen during the heating period.

TABLE III.1

The nomenclature used for the various concrete and mortar mixes having mix proportions as shown (mix proportions by weight).

	Mix Name	Water	Cement	Coarse Agg.	Fine Agg.
CONCRETE	BCY	0,50	1	3,28	2,08
	CCX	0,58	1	3,28	2,08
	CCY	0,58	1	3,90	2,42
MORTAR	BMY	0,50	1	-	2,08
	CMX	0,58	1	-	2,08
	CMY	0,58	1	-	2.42

A typical result sheet as used in APPENDIX II is shown in Table III.2. On every result sheet the mix name, test temperature and treatment (i.e. whether the specimens underwent drying or remained fully saturated during the heating period) is given at the top of the page. Also shown is the initial* water content of the test specimens, W_t, and the respective

* The water content of test specimens immediately prior to heating.

SPECIMEN SERIES : BCY

TEMPERATURE : 100°C

TREATMENT : SATURATED DURING HEATING

INITIAL WATER CONTENT = 304 g = W_t

VIZ. W_c = 134 g = 44,1%; W_n = 93 g = 30,6%; W_g = 77 g = 25,3%

Spec. No.	DEFORMATION			COMPRESSIVE STRENGTH			WATER LOSS					HEAT TREATMENT
	Initial length mm	Strain ** mm/m	Strain *** mm/m	MPa	R.R %		Mass before heat A(g)	Mass after heat B(g)	$\frac{A-B}{W_t}$ %	Mass after wett. C(g)	$\frac{A-C}{W_t}$ %	
1	271,3			53,06			3905					No Heating.
2	273,3			51,08			3900					Tested at
3	268,7			53,49			3896					Room Temp.
Mean 1,2,3	271,3			52,54			3900					
4				40,22	79,0	*						Tested Imm.
5	272,5	0,03		41,77	82,1	**	3960	3956	1,3			Max. Temp.
6	273,3	0,04	0,03	45,91	90,2	***	3932	3927	1,6	3932	0,0	Attained (Time T)
7				40,31	79,2	*						Tested At
8	270,3	0,04		40,57	79,7	**	3852	3847	1,6			T + 12 hrs
9	270,5	0,05	0,03	45,99	90,4	***	3901	3896	1,6	3900	+0,3	
10				42,89	84,3	*						Tested At
11	273,1	0,05		44,18	86,8	**	3893	3889	1,3			T + 24 hrs
12	270,3	0,06	0,05	46,17	90,7	***	3826	3821	1,6	3826	0,0	
13				42,81	84,1	*						Tested At
14	272,0	0,06		45,82	90,0	**	3896	3891	1,6			T + 36 hrs
15	275,1	0,07	0,06	47,03	92,4	***	3961	3975	1,3	3962	-0,3	
16				44,53	87,5	*						Tested At
17	271,3	0,07		47,54	93,4	**	3914	3909	1,6			T + 36 hrs
18	275,1	0,07	0,06	48,23	94,8	***	3974	3970	1,3	3975	-0,3	+ 1 cycle
19				43,93	86,3	*						Tested At
20	273,3	0,06		48,41	95,1	**	3940	3935	1,6			T + 36 hrs
21	271,8	0,05	0,05	48,58	95,4	***	3961	3958	1,0	3963	-0,7	+ 2 Cycles
22						*						Tested At
23	274,8	0,07		46,42		**	3966	3955	3,6			T + 36 hrs
24	271,5	0,04	0,04	47,97		***	3894	3888	2,0	3893	+0,3	+ 2 Cycles
Mean 1-24	272,5						3919					

* TESTED HOT

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE III.2

SPECIMEN SERIES : BCY

TEMPERATURE : 100°C

TREATMENT : SATURATED DURING HEATING

Spec. No.	PULSE VELOCITY				DYNAMIC YOUNG'S MODULUS				POISSON'S RATIO			
	* m/sec	** and *** m/sec	R.R %		* GPa	** and *** GPa	R.R %		*	** and ***	R.R %	
1	4674				38,62				0,314			
2	4792				38,35				0,328			
3	4703				39,20				0,315			
Mean of 1,2,3	4724				38,72				0,319			
4												
5	4763	4646	97,4	**	38,74	35,95	89,9	**	0,327	0,334	105,7	**
6	4733	4618	96,8	***	37,97	35,93	89,5	***	0,326	0,328	103,8	***
7												
8	4792	4618	96,8	**	37,33	34,00	85,0	**	0,335	0,340	107,6	**
9	4792	4618	96,8	***	39,19	36,81	92,0	***	0,325	0,322	101,9	***
10												
11	4763	4590	96,2	**	37,86	33,71	84,3	**	0,328	0,339	107,3	**
12	4792	4704	98,6	***	38,71	35,60	89,0	***	0,323	0,336	106,3	***
13												
14	4763	4646	97,4	**	37,35	35,04	87,6	**	0,333	0,336	106,3	**
15	4792	4563	95,6	***	38,29	36,18	90,4	***	0,331	0,319	100,9	***
16												
17	4733	4646	97,4	**	39,14	35,46	88,7	**	0,318	0,335	106,0	**
18	4763	4646	97,4	***	38,27	36,67	91,7	***	0,329	0,327	103,5	***
19												
20	4792	4646	97,4	**	38,62	35,60	89,0	**	0,329	0,334	105,7	**
21	4792	4675	98,0	***	38,61	37,09	92,7	***	0,332	0,330	104,4	***
22												
23	4763	4646		**	38,05	35,55		**	0,330	0,334		**
24	4792	4704		***	38,41	36,88		***	0,329	0,330		***
Mean of 1-24	4773				38,32				0,328			

* TESTED BEFORE HEATING

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE III.2 (contd.)

quantities of capillary water, W_c, water in the gel pores, W_g, and chemically combined water, W_n. (The method of calculating W_t, W_c, W_g and W_n is given in APPENDIX I.4.) The result sheet illustrated in Table III.2 shows that the test specimens which were used for a series of tests at a particular temperature were numbered from 1 to 24. The test specimens were tested as follows:-

Immediately prior to heating, the following tests were performed on all the test specimens except those that were to be tested whilst hot, viz. on all specimens except No. 4, 7, 10, 13, 16 and 19.

(i) The length of each specimen was determined using the Apparatus described in PART II, CHAPTER 4.

(ii) The mass of each test specimens was determined.

(iii) The ultrasonic pulse velocity was measured at three different positions along the length of the test specimen.

(iv) Three determinations of the fundamental longitudinal frequency of vibration of the test specimens were carried out, the test specimen having been removed from the apparatus and replaced for each successive measurement. Using the longitudinal frequency of vibration and the data obtained from (i) and (ii) above, the dynamic Young's modulus was calculated. The method of calculating dynamic Young's modulus is given in APPENDIX I.1.

(v) Poisson's ratio was calculated using the data from measurements (i) to (iv) above. The method of calculating Poisson's ratio is given in APPENDIX I.2.

(It should be noted that for each test specimen only the mean value of the pulse velocity, the mean value of the dynamic Young's modulus and the mean value for Poisson's ratio are given on the result sheets.)

Control tests for compressive strength were performed on test specimens No.1, No. 2 and No. 3. Two modified compression tests were carried out on each test specimen. Only the mean of the two modified compression tests on the respective specimens is reported on the data sheets.

In the test series in which the specimens were allowed to dry during heating, test specimens No. 23 and No. 24 were heated in Furnace No. 1. The linear deformation and water loss, respectively, of these specimens was continuously monitored during the heating period. Test specimens No. 4 to No. 21 were heated in Furnace No. 2 and removed in batches of three specimens at various times during the heating period, e.g. test specimens No. 4, No. 5 and No. 6 were removed from Furnace No. 2 immediately that the desired temperature level had been attained. Two modified compression tests were performed on test specimen No. 4 whilst hot. Test specimens No. 5 and No. 6 were cooled to the datum temperature and the tests (i) to (v) above were carried out. Specimen No. 5 was then subjected to two modified compression tests, and test specimen No. 6 was placed in a waterbath at 30°C for seven days. At the end of this period test specimen No. 6 was subjected to tests (i) to (v) above, whereupon two modified compression tests were performed on this test specimen. A similar test procedure was followed for successive batches of test specimens removed from Furnace No. 2. The result sheets clearly indicate the time at which a particular test specimen was removed from Furnace No. 2 and whether the test specimen was tested hot, tested after cooling or tested after seven days in water. It should be noted that test specimen No. 22 was left to cure (21°C and 100% R.H.) for a further three days. After specimens No. 23 and No. 24 had been removed from Furnace No. 1 at the end of the heating and temperature cycling period, test specimen No. 22 was used for a duplicate test of linear deformation during heating.

The heating and testing procedure adopted for the test specimens which remained fully saturated during the heating period differed from the heating procedure for specimens which underwent drying in only one respect. The difference was that test specimen No. 23 was not heated in Waterbath No. 1 together with the test specimen (No. 24) on which the linear deformation was monitored during heating, i.e. test specimen No. 23 was heated in Waterbath No. 2 together with specimens No. 4 to No. 21.

Each set of results in APPENDIX II (Table A.II.1 to Table A.II.42) are for only one series of tests of a particular mix at a particular temperature, i.e. no repeat tests with independent sets of specimens were performed. However, the ultrasonic pulse velocity, dynamic Young's modulus and Poisson's ratio values are the mean of three determinations on a particular test specimen, and the compressive strength values are the mean of two modified compression tests on a particular test specimen, i.e. by replicating these

tests the experimental error due to test procedure is partly eliminated. Furthermore, it should be remembered that specimens were tested at various times during the heating period. Using the statistical technique known as analysis of variance * it may be determined from these results whether;

(i) the various properties underwent significant changes between successive tests at the various test times during the heating period.

(ii) the various concrete or mortar mixes exhibit significantly different behaviour of a particular property at a particular temperature.

Furthermore, by using a statistical method of multiple comparisons (Tukey's method) ** it is possible to determine also;

(i) whether, in general, the concrete mixes underwent greater property reduction than the mortar mixes.

(ii) whether a change in the water content between two concrete mixes (BCY and CCX), or two mortar mixes (BMY and CMX), affect the property behaviour of heated test specimens.

(iii) whether a change in the volumetric concentration of aggregate between two concrete mixes (CCX and CCY), or two mortar mixes (CMX and CMY), affects the property behaviour of heated test specimens.

The information that was obtained by adopting the above approach, i.e. only one series of tests,on a particular mix at each test temperature,over a range of concrete and mortar mixes, was of greater value than data which could have been obtained from repeat tests on fewer mixes. The disadvantage of using this approach occurs if an error is made in the manufacture of a set of test specimens. However, errors of this nature could be determined from the control tests and is discussed in CHAPTER 1 : PROPERTIES OF HARDENED CONCRETE AND MORTAR MIXES.

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* The statistical method is given in references 77; 78; 79 and 80.

** The statistical method is given in references 77 and 81.

The data in APPENDIX III, Figure A.III.1 to Figure A.III.12, is for water loss monitored continuously one one test specimen during heating of the various concrete and mortar mixes. In Figure III.1 some typical water loss vs. time curves are shown for concrete test specimens (Mix BCY) at temperatures of 70°C, 100°C and 150°C respectively. The water loss is expressed as a percentage of the total amount of water (W_t) contained in the test specimens before heating*.

The results of linear deformation measurements on heated concrete and mortar specimens are illustrated graphically in APPENDIX IV, Figure A.IV.1 to Figure A.IV.42. A typical graph of linear deformation plotted against time is shown in Figure III.2 for a mortar specimen (Mix CMX) heated to 150°C. All results of linear deformation during heating are the mean of two independent determinations. It must be pointed out, though, that the test specimen used for the duplicate test had been cured for 31 days. However, preliminary tests indicated that there was no significant difference between the linear deformation of heated test specimens which had been cured for 28 days and 31 days respectively. Before calculating the mean linear deformation curve, all the graphs of linear deformation during heating were corrected for small fluctuations of the test specimen average temperature about the desired temperature level. The correction method is given in APPENDIX I.5.

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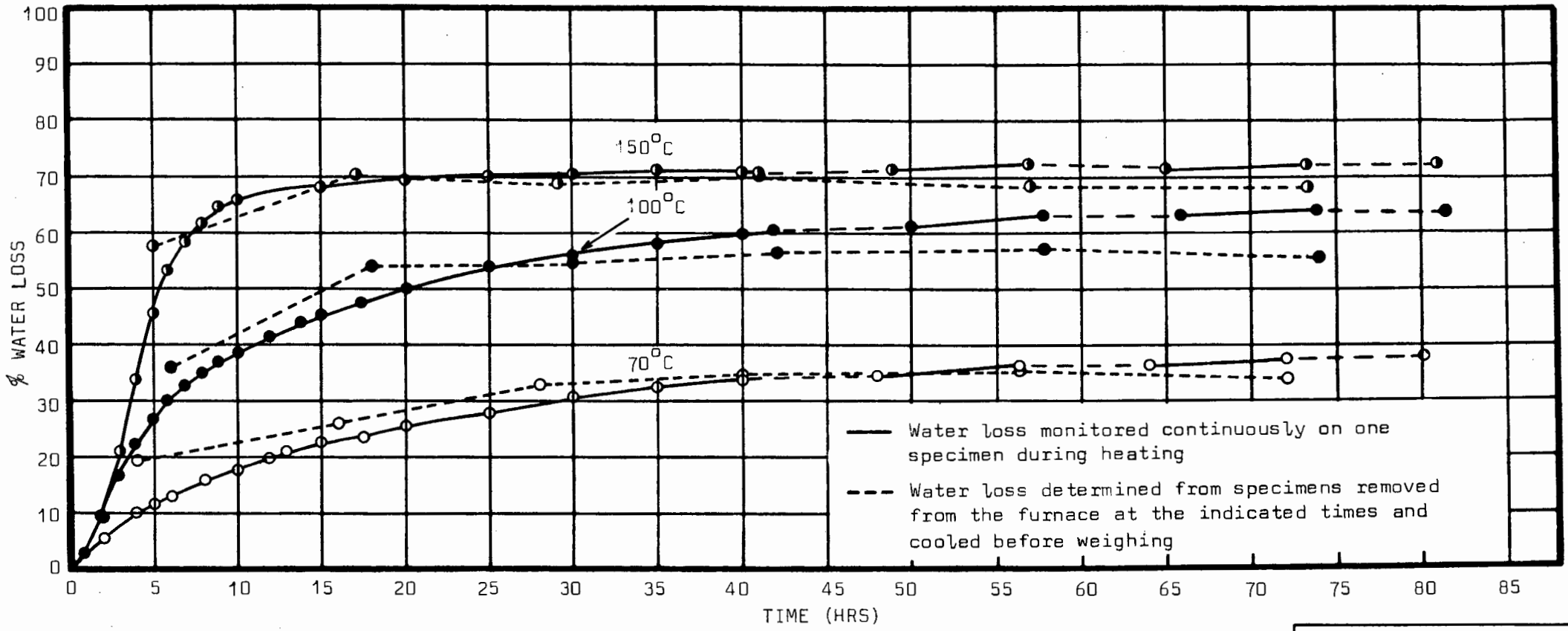
* The method of calculating W_t is given in APPENDIX I.4.



																				Temperature Cycling				
TIME(HRS)	0	1	2	3	4	5	6	7	8	9	10	12	14	16	20	25	30	35	40	C	H	C	H	C
70°C	0	3,0	5,4	7,8	9,6	11,2	12,8	14,1	15,8	16,8	17,8	19,5	21,6	17,9	25,5	27,6	30,5	32,4	33,8	34,5	36,2	36,5	37,6	38,1
100°C	0	3,6	9,8	17,1	22,8	26,8	30,4	33,1	35,1	37,2	39,0	41,8	44,5	46,5	50,4	54,0	56,5	58,2	59,5	61,1	63,3	63,3	64,1	63,6
150°C	0	3,0	9,3	20,7	33,8	45,4	53,2	58,2	61,9	64,1	65,6	66,3	67,6	68,0	69,1	70,0	70,1	70,1	70,3	71,1	72,0	71,1	71,9	72,0

Values for water loss monitored continuously on one specimen during heating.

FIG.III.1: Water loss at temperatures of 70°C,100°C, and 150°C: Mix BCY

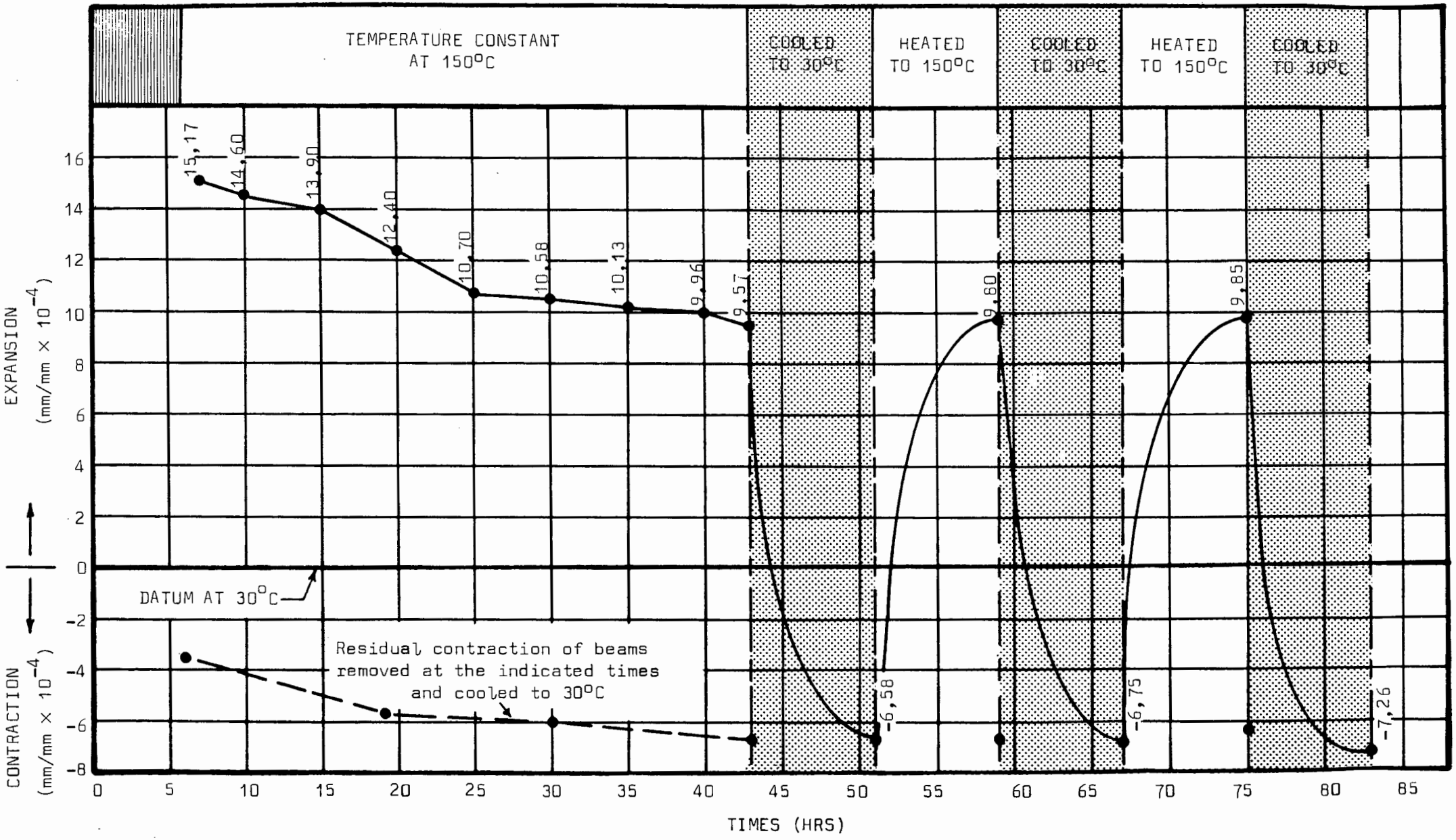


FIG.III.2: The linear deformation of test specimen: Mix CMX at 150°C (dry).

CHAPTER 1 : PROPERTIES OF THE HARDENED CONCRETE AND MORTAR MIXES

The compressive strength and dynamic Young's modulus of unheated test specimens were the control parameters in this investigation. For every mix it was ascertained whether the sets of specimens that were tested at the various temperature levels were from the normal population of all test specimens of that particular mix. This was done by choosing, at random, a sample of specimens from the test specimens that were used for a series of tests at a particular temperature and determining the mean compressive strength and the mean dynamic Young's modulus of these (unheated) specimens. For the compressive strength these control specimens were specimens Nos. 1, 2 and 3; for the dynamic Young's modulus the specimens No. 1 to No. 24 were used, excluding specimens No. 4, No. 7, No. 10, No. 13, No. 16, No. 19 and No. 22. Similar control tests were performed on the respective sets of specimens that were to be tested at the different temperature levels. * At the end of the experimental programme the mean values of the compressive strength control tests and the mean values of the dynamic Young's modulus control tests (ie. for the respective sets of specimens of a particular mix tested at the various temperature levels) were plotted on probability paper to test for normality. The extreme values of the data were tested as outlying observations and outlying observations were rejected at a 99% confidence level. [75, 76] If an outlying observation occured, it was assumed that an error had been made in the manufacture of that particular set of test specimens. Consequently, all the data pertaining to that set of test specimens was discarded and the experimental work repeated. When this data became available the procedure of determining normality and testing for outlying observations of the extreme values was repeated.

In Figure III.3 to Figure III.8 the probability distribution of the compressive strength control values and the dynamic Young's modulus control values of the various concrete and mortar mixes are illustrated. An outlying observation occurred in only one instance, viz. for the dynamic Young's

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* There were five different temperature levels (70°C, 100°C, 150°C, 250°C and 400°C) at which test specimens underwent drying during heating, and two temperature levels (70°C and 100°C) at which specimens remained fully saturated during heating. Consequently, seven sets of test specimens of a particular mix had been made during the course of the investigation.

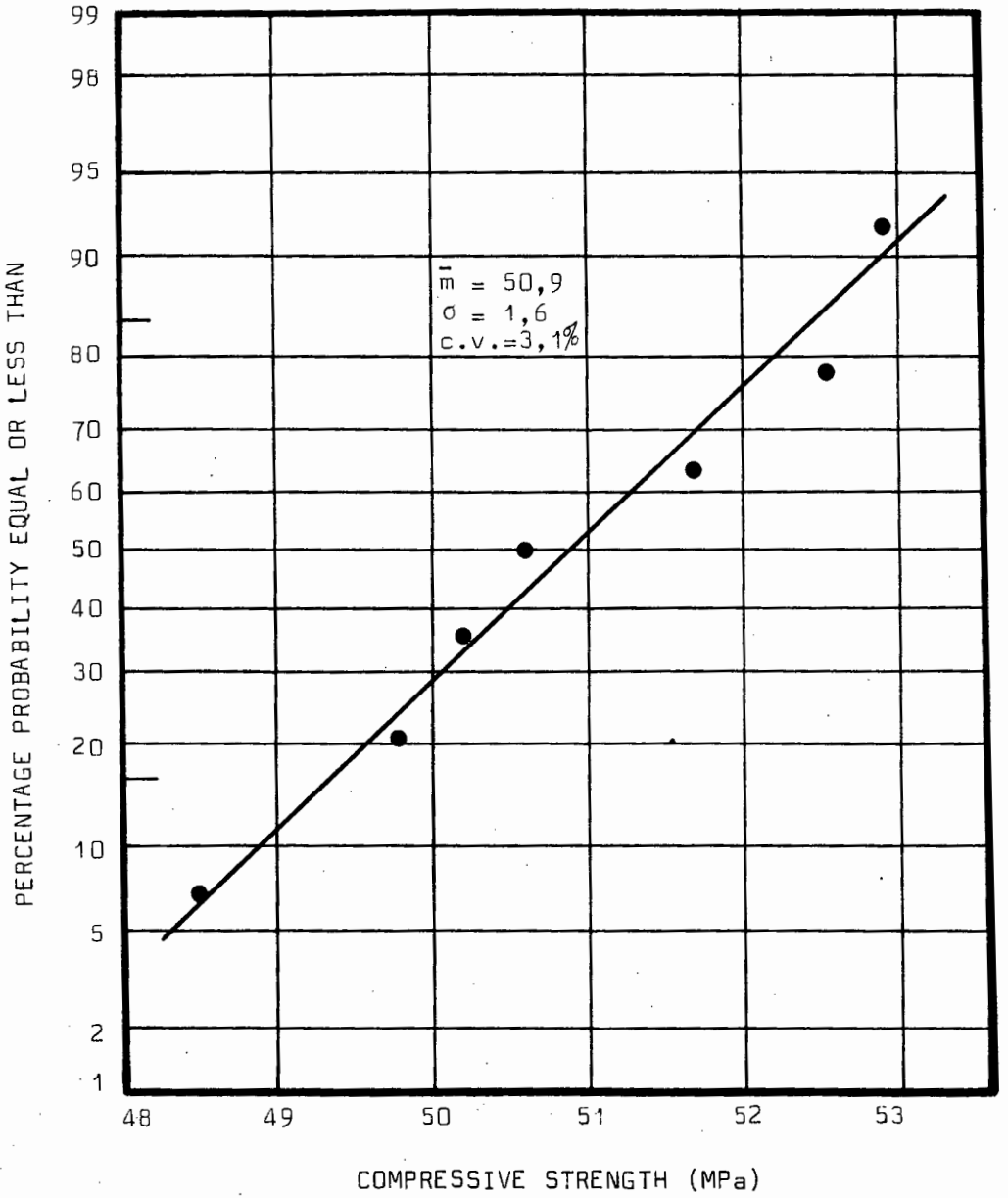

FIG.III.3 (a): The probability distribution of the compressive strength control values for test specimens made from Mix BCY.

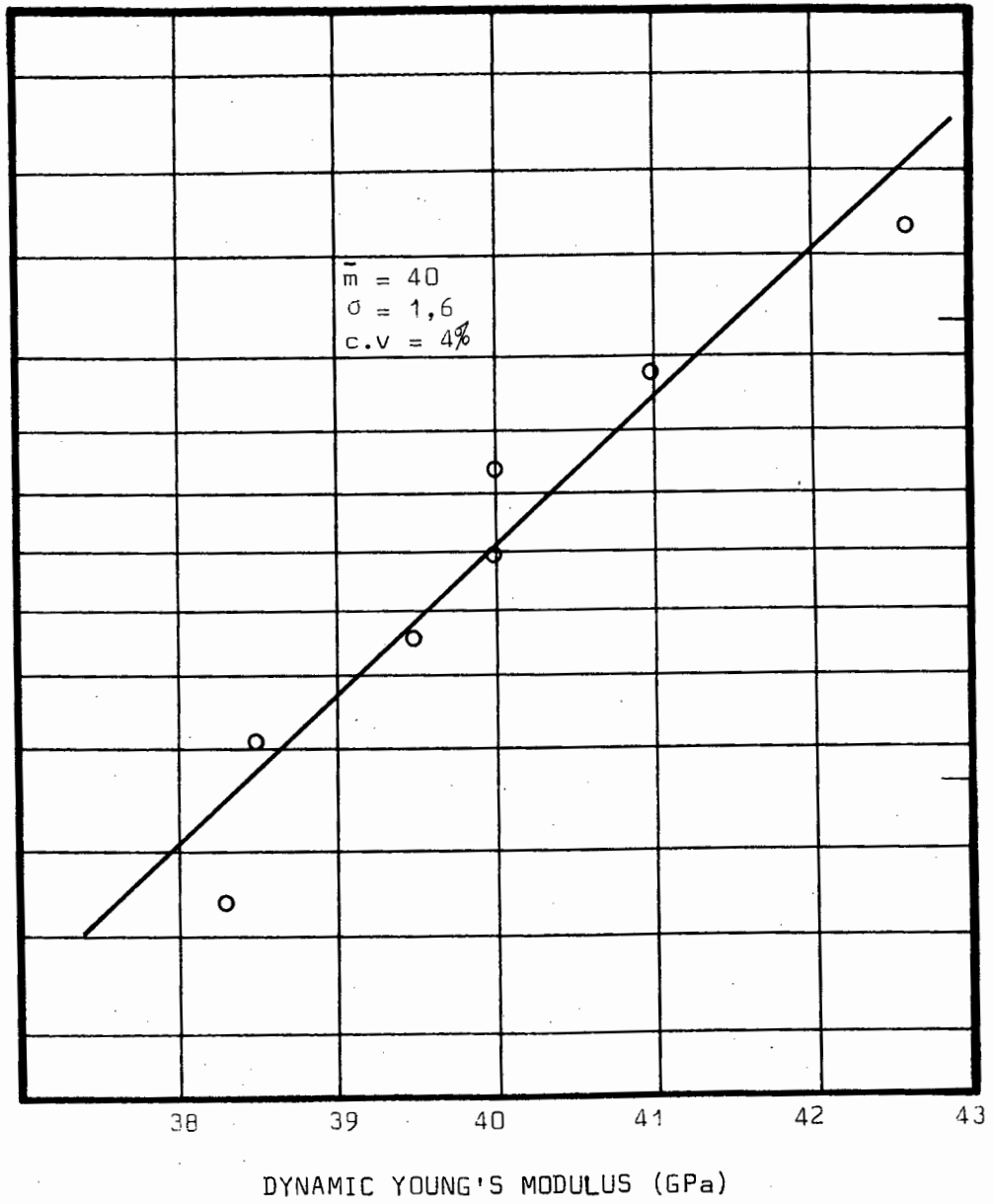

FIG.III.3 (b): The probability distribution of the dynamic Young's Modulus control values for test specimens made from Mix BCY.

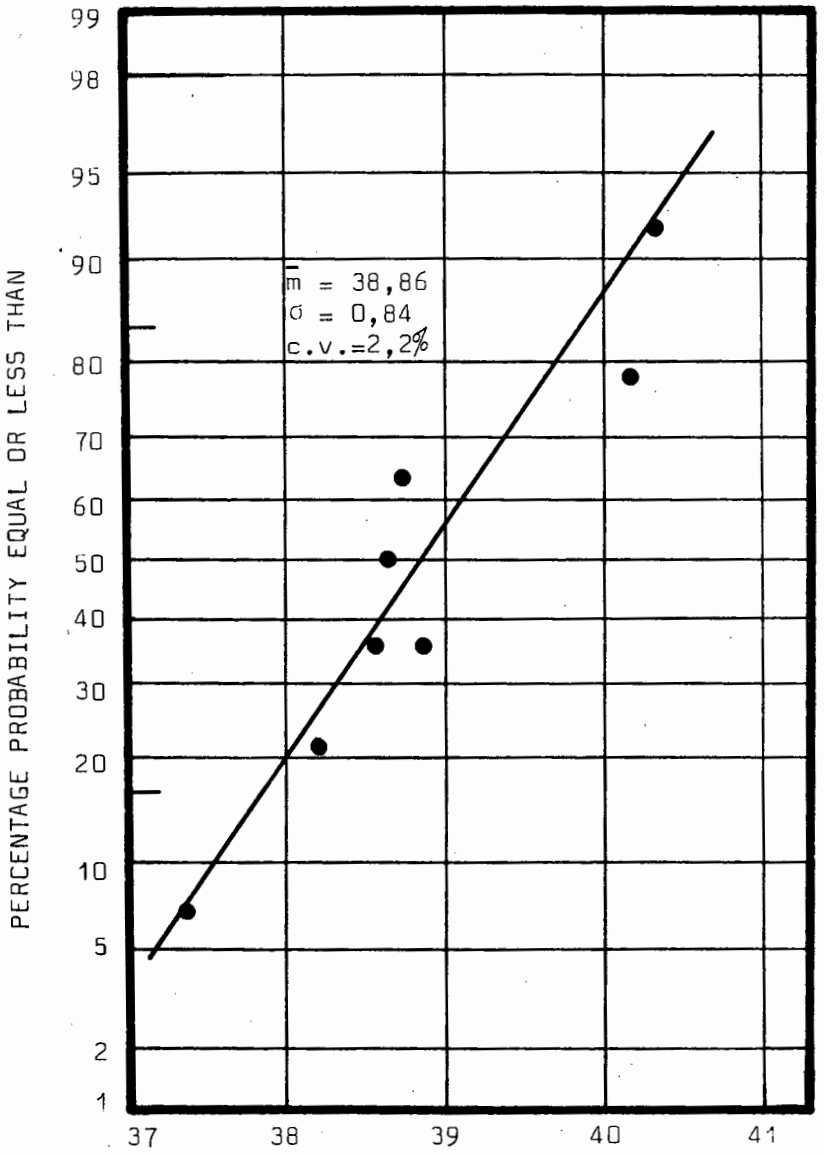

FIG.III.4 (a): The probability distribution of the compressive strength control values for test specimens made from Mix CCX.

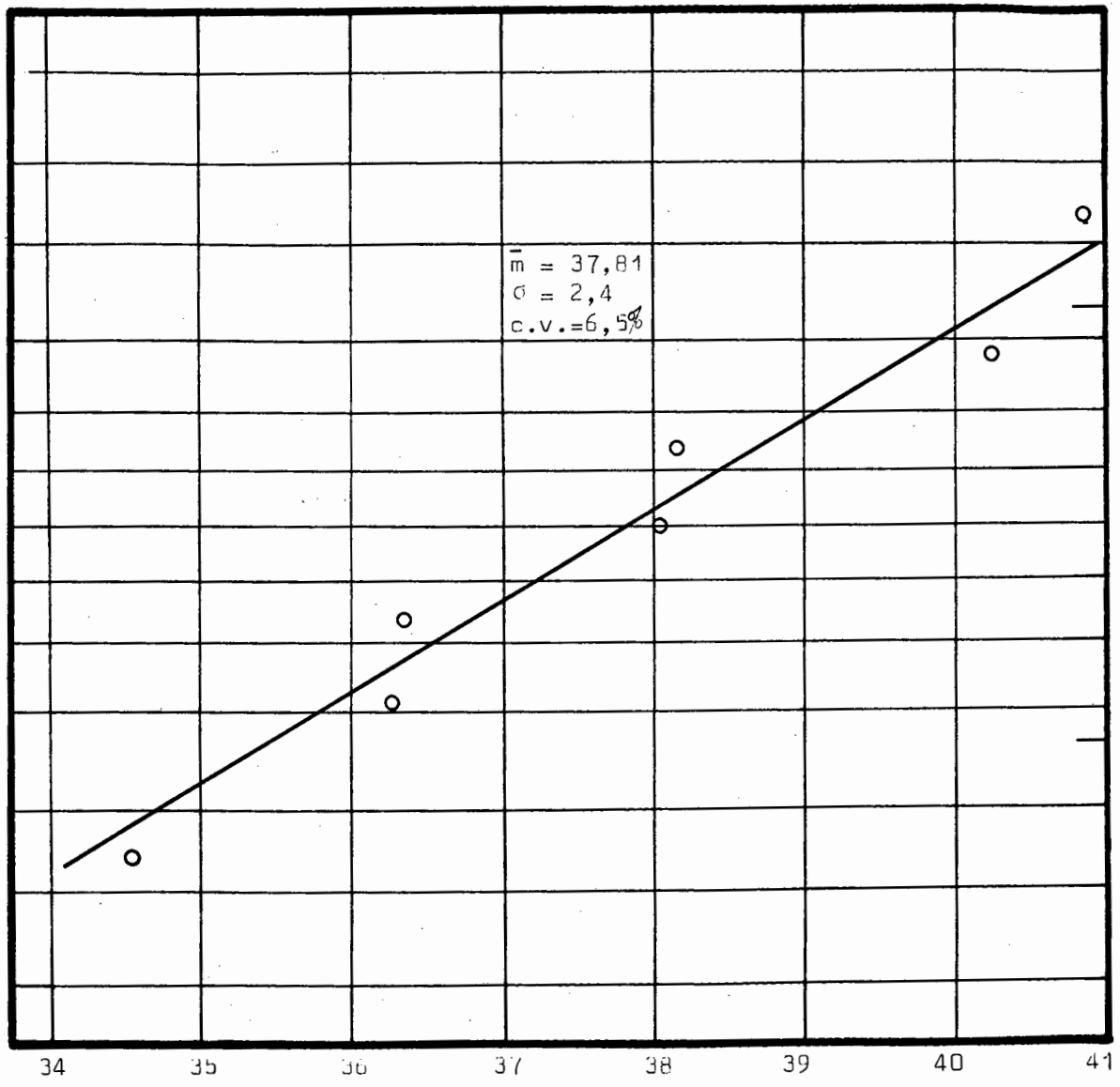

FIG.III.4 (b): The probability distribution of the dynamic Young's Modulus control values for test specimens made from Mix CCX.

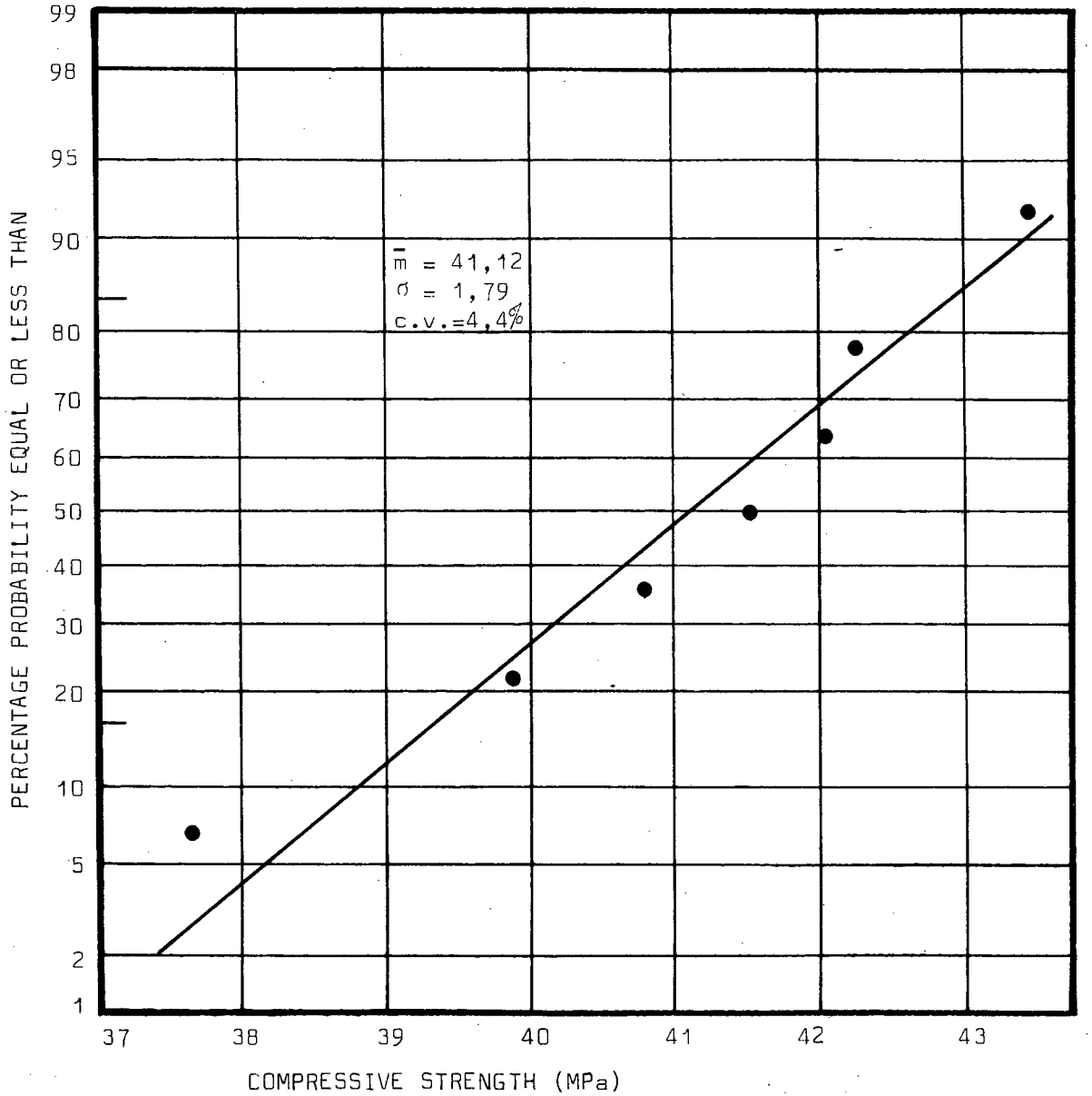

FIG.III.5 (a): The probability distribution of the compressive strength control values for test specimens made from Mix CCY.

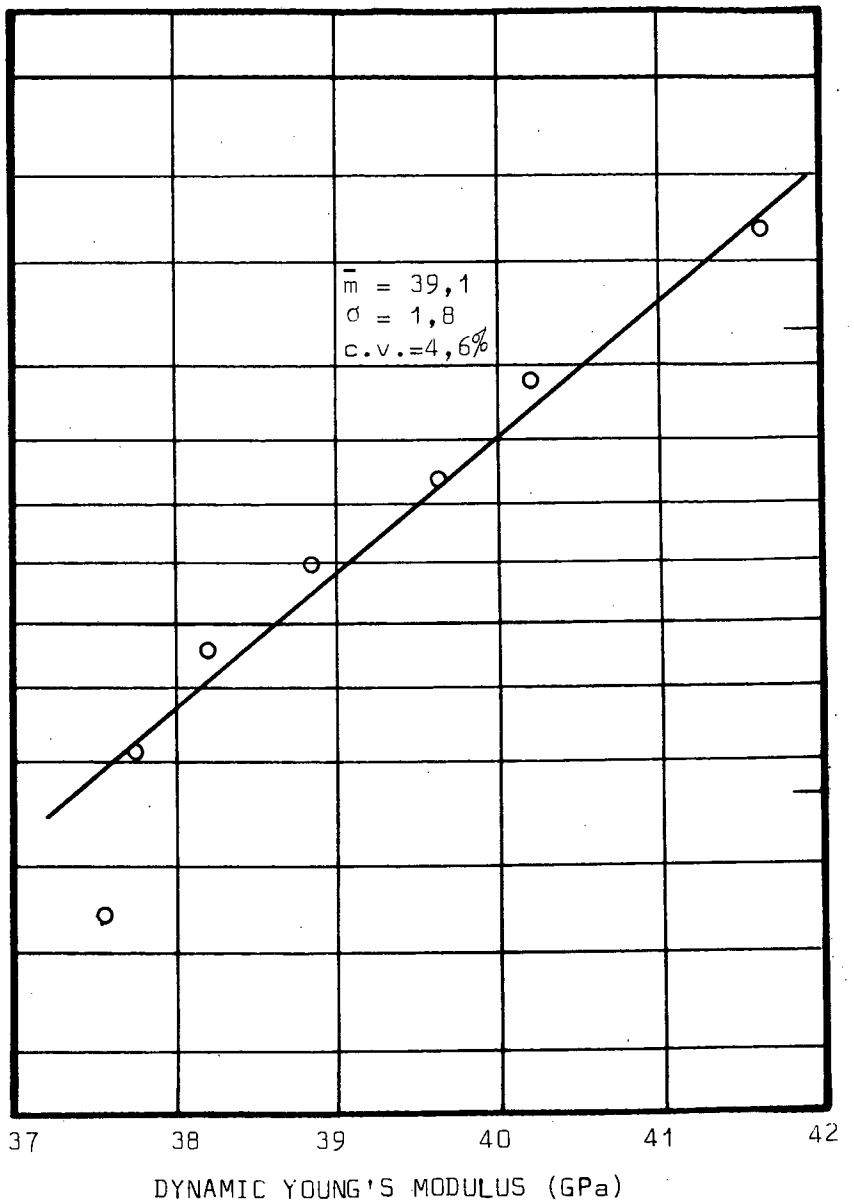

FIG.III.5 (b): The probability distribution of of the dynamic Young's Modulus control values for test specimens made from Mix CCY.

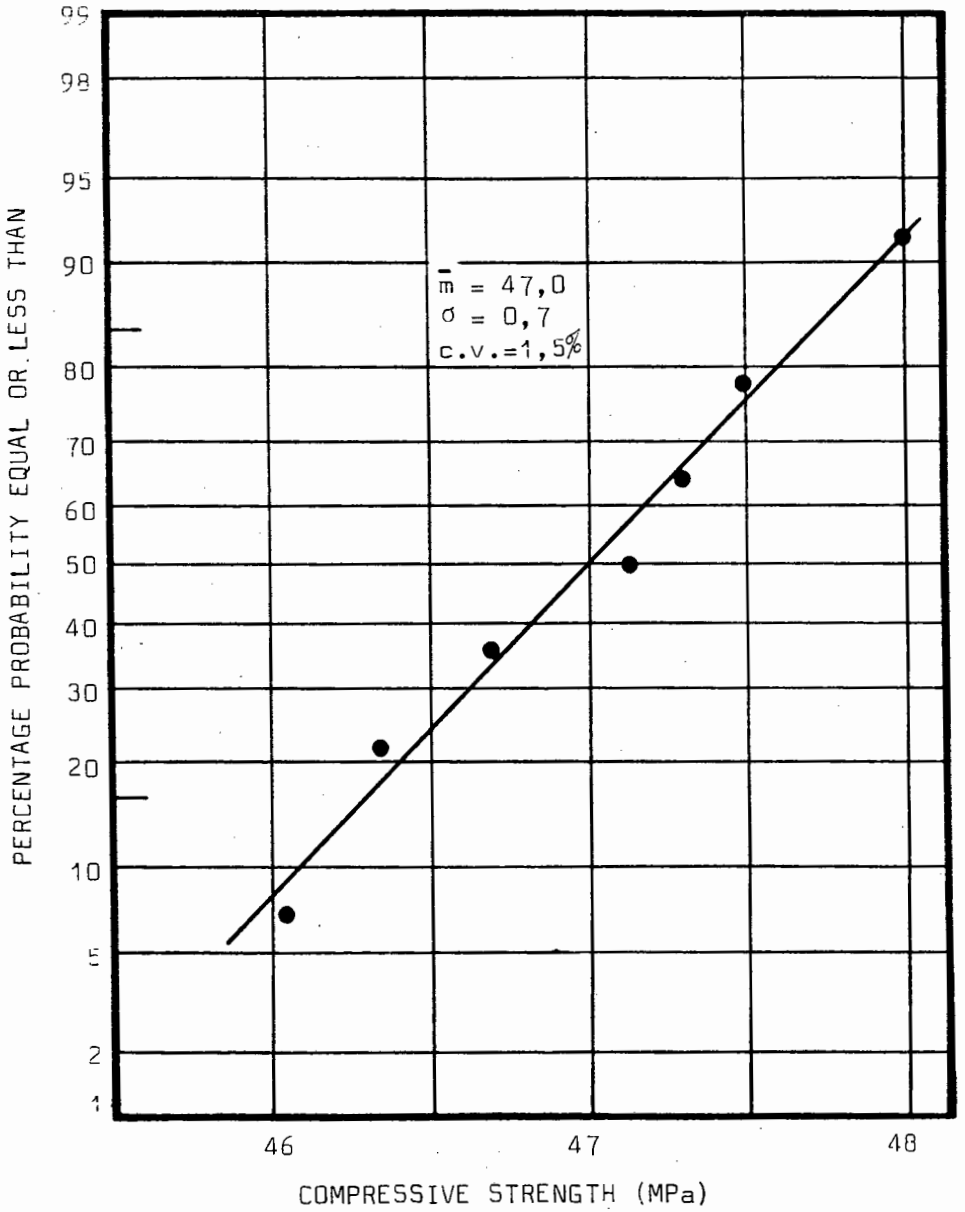

FIG.III.6 (a): The probability distribution of the compressive strength control values for test specimens made from Mix BMY.

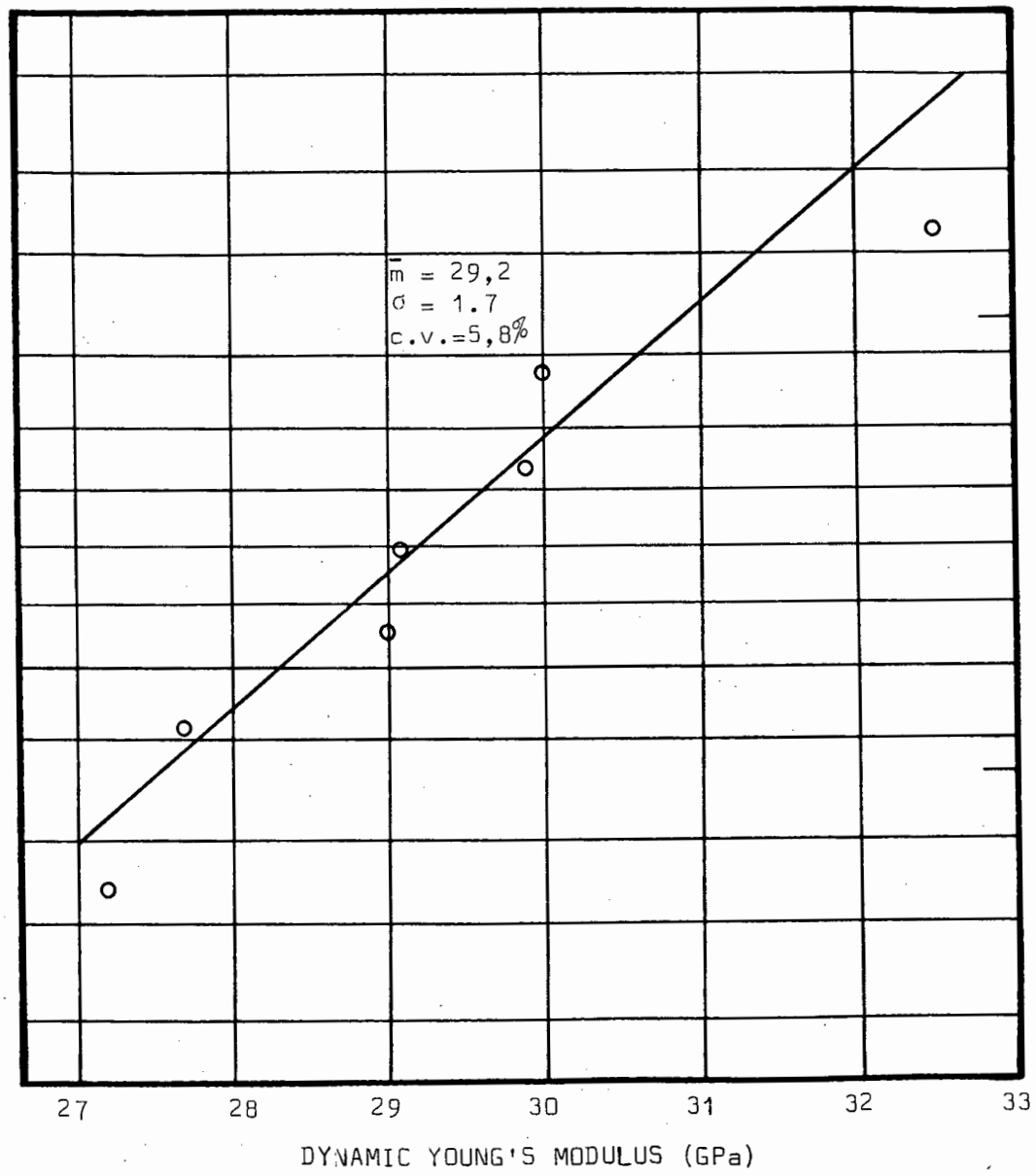

FIG.III.6 (b): The probability distribution of the dynamic Young's Modulus control values for test specimens made from Mix BMY.

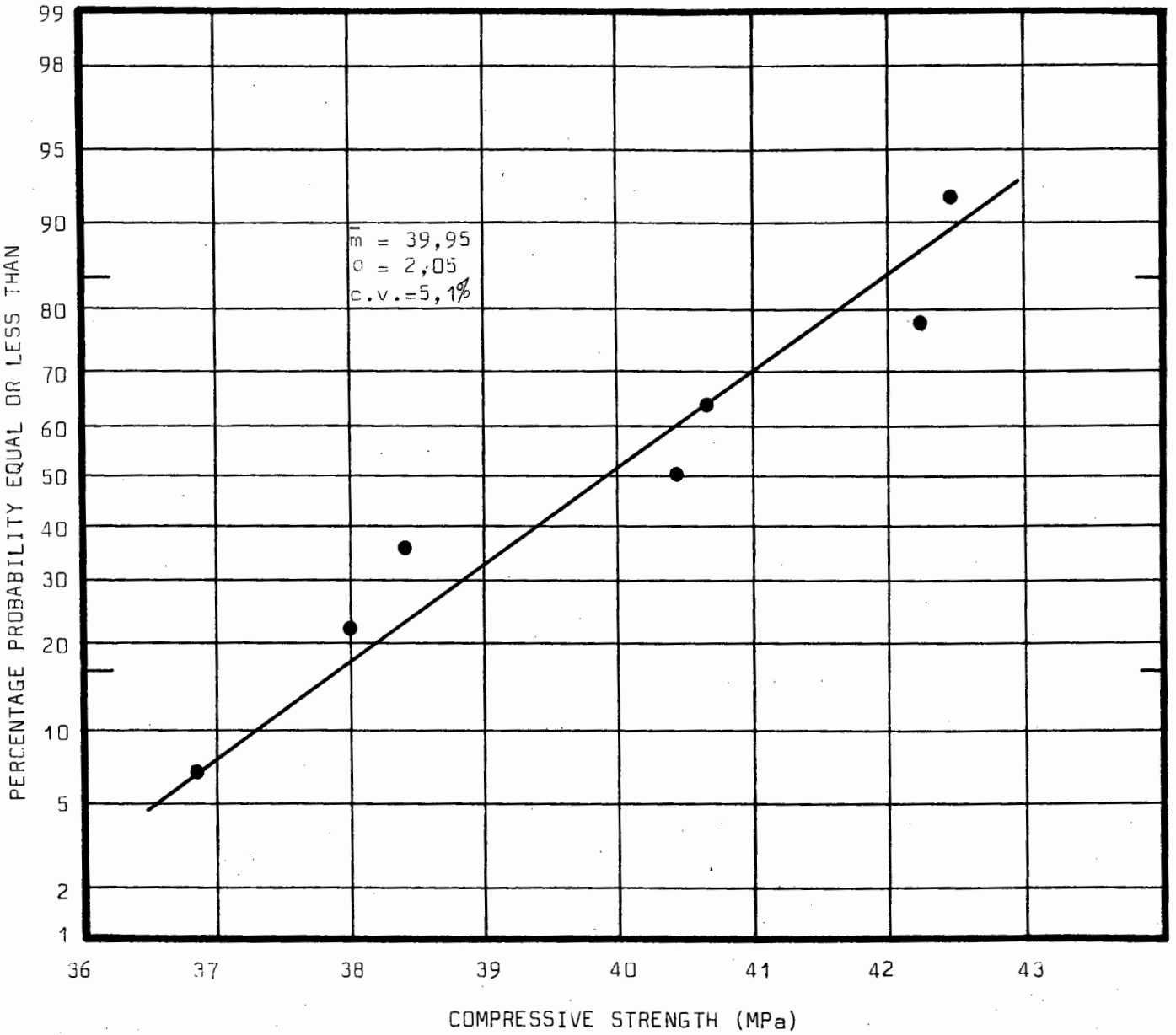

FIG.III.7 (a): The probability distribution of the compressive strength control values for test specimens made from Mix CMX.

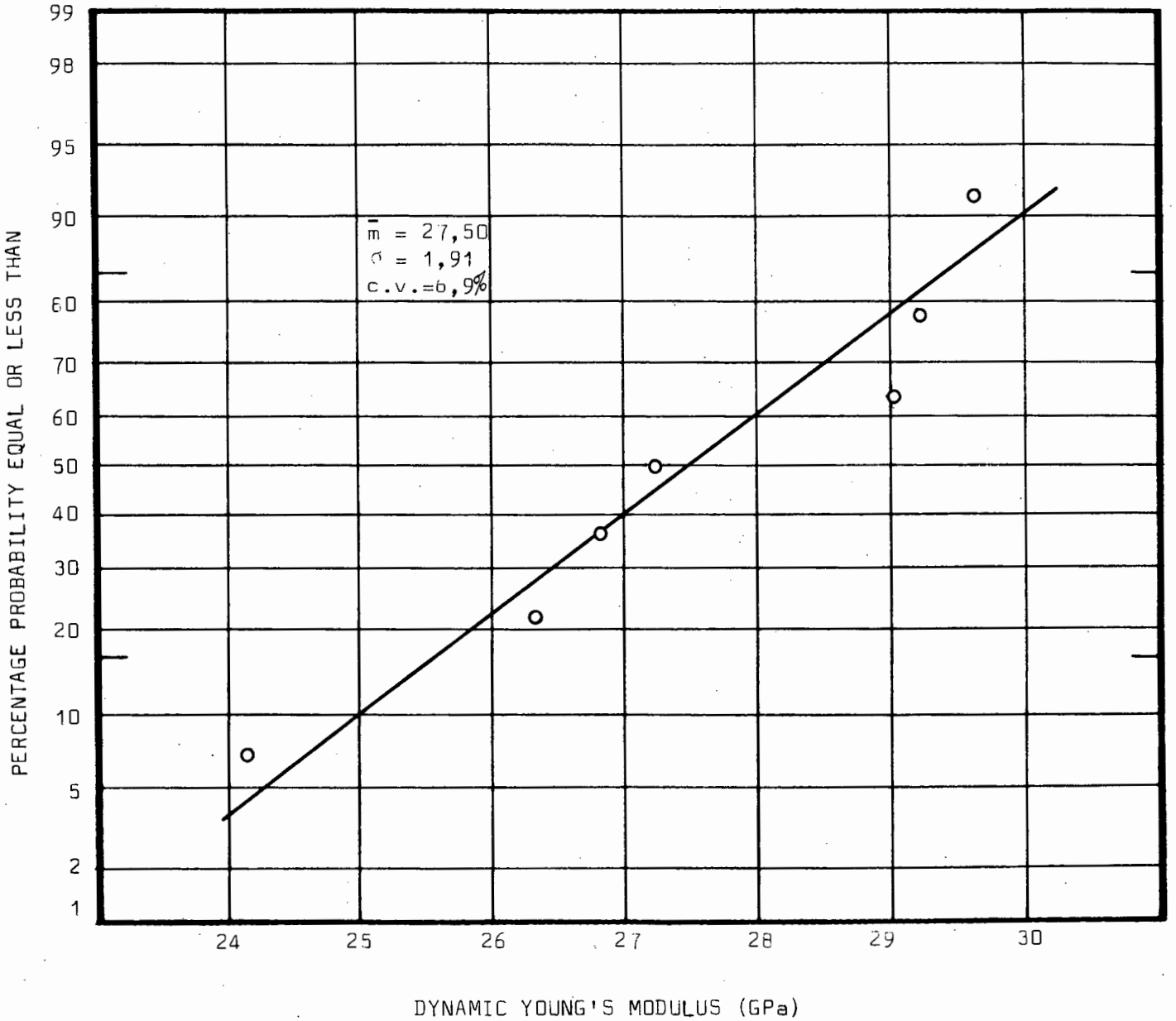

FIG.III.7 (b): The probability distribution of the dynamic Young's Modulus control values for test specimens made from Mix CMX.

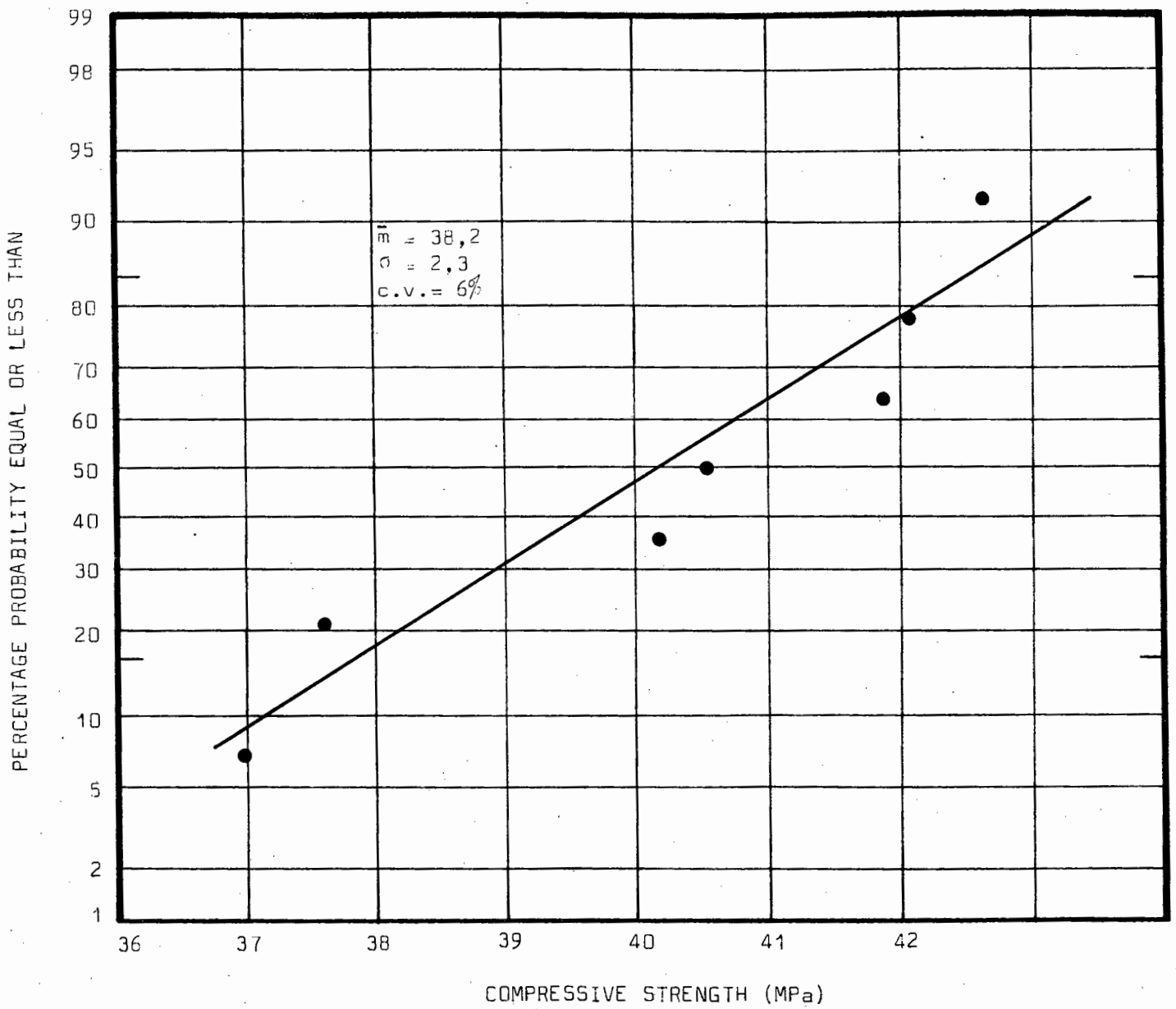

FIG.III.8 (a): The probability distribution of the compressive strength control values for test specimens made from Mix CMY.

modulus control values of the mortar mix CMY that underwent drying at a temperature of 150°C. The data illustrated for mix CMY in Figure III.8 do not show this outlying observation, i.e. the probability distributions for compressive strength and dynamic Young's modulus respectively, contain the control value which replaced the outlying data. The extreme values of the re-plotted data were again tested as outlying observations; no further outliers occurred.

From each probability distribution illustrated in Figure III.3 to Figure III.8, a population mean, standard deviation and coefficient of variation was determined. These values are shown in Table III.3 and indicate that there was little variation between the respective sets of test specimens made from a particular mix during the course of the investigation. *

TABLE III.3

The mean compressive strength and mean dynamic Young's modulus of the hardened concrete and mortar mixes prior to heating.

	MIX NAME	COMPRESSIVE STRENGTH			DYNAMIC YOUNG'S MODULUS		
		MEAN MPa	STD.DEV. MPa	COEFF. OF VAR. %	MEAN GPa	STD.DEV. GPa	COEFF. OF VAR. %
CONCRETE MIXES	BCY	50,90	1,60	3,1	40,0	1,60	4,0
	CCX	38,86	0,84	2,2	37,81	2,41	6,5
	CCY	41,12	1,79	4,4	39,09	1,78	4,6
MORTAR MIXES	BMY	47,00	0,70	1,5	29,20	1,70	5,8
	CMX	39,95	2,05	5,1	27,50	1,91	6,9
	CMY	38,20	2,32	5,9	28.40	1,90	6,7

Calculated values of the population mean, the standard deviation and the coefficient of variation for the pulse velocity determinations that were performed on test specimens prior to heating, are given in Table III.4. In general, the coefficient of variation of the pulse velocity measurements on test specimens of a particular mix is smaller than the coefficient of variation of either the compressive strength or the dynamic Young's modulus values. Also shown in Table III.4 are calculated population mean values for Poisson's ratio of test specimens made from the various mixes. No

* The duration of the experimental programme was approximately one year.

standard deviation values or coefficients of variation are given for Poisson's ratio. This is because Poisson's ratio is calculated from two normal populations (dynamic Young's modulus and pulse velocity), and the resulting ratio need not necessarily be normally distributed.

TABLE III.4

The mean values of ultrasonic pulse velocity and Poisson's ratio for unheated specimens made from the various concrete and mortar mixes.

	MIX NAME	ULTRASONIC PULSE VELOCITY			POISSON'S RATIO
		MEAN m/sec	STD.DEV. m/sec	COEFF.OF VAR. (%)	
CONCRETE MIXES	BCY	4772	40,7	0,85	0,316
	CCX	4612	97,0	2,10	0,310
	CCY	4682	21,3	0,40	0,309
MORTAR MIXES	BMY	4119	61,6	1,50	0,293
	CMX	3987	26,0	0,60	0,291
	CMY	3995	69,6	1,70	0,280

Each population mean reported in Table III.3 and Table III.4 is assumed to be the best estimate of the mean for the particular property of unheated test specimens of the various mixes. Subsequent references to 'mean values' apply to the values reported above.

CHAPTER 2 : THE COMPRESSIVE STRENGTH OF HEATED CONCRETE AND MORTAR SPECIMENS

The compressive strength data for specimens made from the various concrete and mortar mixes and tested at the different temperature levels are shown in APPENDIX II, Table A.II.1 to Table A.II.42. For a particular compressive strength test both the value of compressive strength (MPa) and the residual ratio of the compressive strength are given. The residual ratio of compressive strength is the ratio of the compressive strength of a heated test specimen to the mean compressive strength of that particular mix, expressed as a percentage. (The mean compressive strength for a particular mix is that reported in CHAPTER 1.)

The residual ratio of compressive strength for specimens tested whilst hot at the different temperature levels, is shown in Figure III.9 for the concrete mix BCY and the corresponding mortar mix BMY. * The data for the test specimens which underwent drying during heating, as well as the data for specimens which remained fully saturated during heating, are shown. In each case the maximum residual ratio and the minimum residual ratio that occurred during the period when the temperature remained constant is plotted, i.e. the data on specimens tested during temperature cycling is not included. Figure III.10 illustrates the residual ratios of compressive strength for the test specimens (mixes BCY and BMY) which were cooled before testing, and Figure III.11 the residual ratios for test specimens which were cooled and then stored in water for 7 days prior to testing.

The compressive strength data obtained from the concrete mix CCX and corresponding mortar mix CMX, and the concrete mix CCY and corresponding mortar mix CMY, are plotted in exactly the same way as the data for mixes BCY and BMY. In Figure III.12, Figure III.13 and Figure III.14 respectively, the residual ratios of compressive strength for mixes CCX and CMX are shown for test specimens tested whilst hot, test specimens cooled before testing, and for the case where the test specimens were cooled and immersed in water for 7 days before testing. The data for mixes CCY and CMY are shown in Figure III.15, Figure III.16 and Figure III.17 for the abovementioned respective test cases.

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* The concrete mix BCY and the mortar mix BMY differed only in that the mortar mix contained no coarse aggregate.

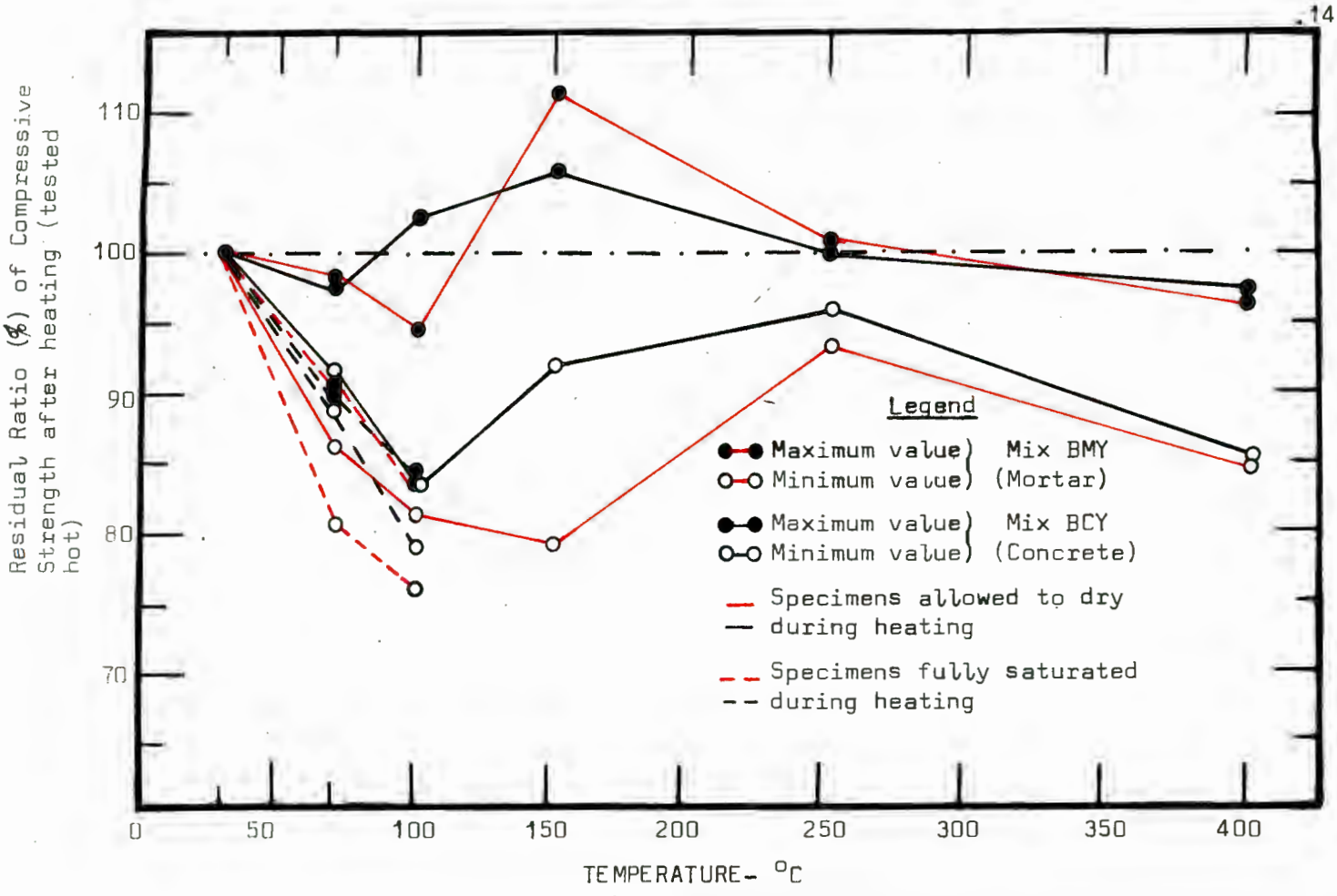


FIG.III.9: The residual ratio (%) of compressive strength for specimens tested whilst hot : Mixes BCY and BMY.

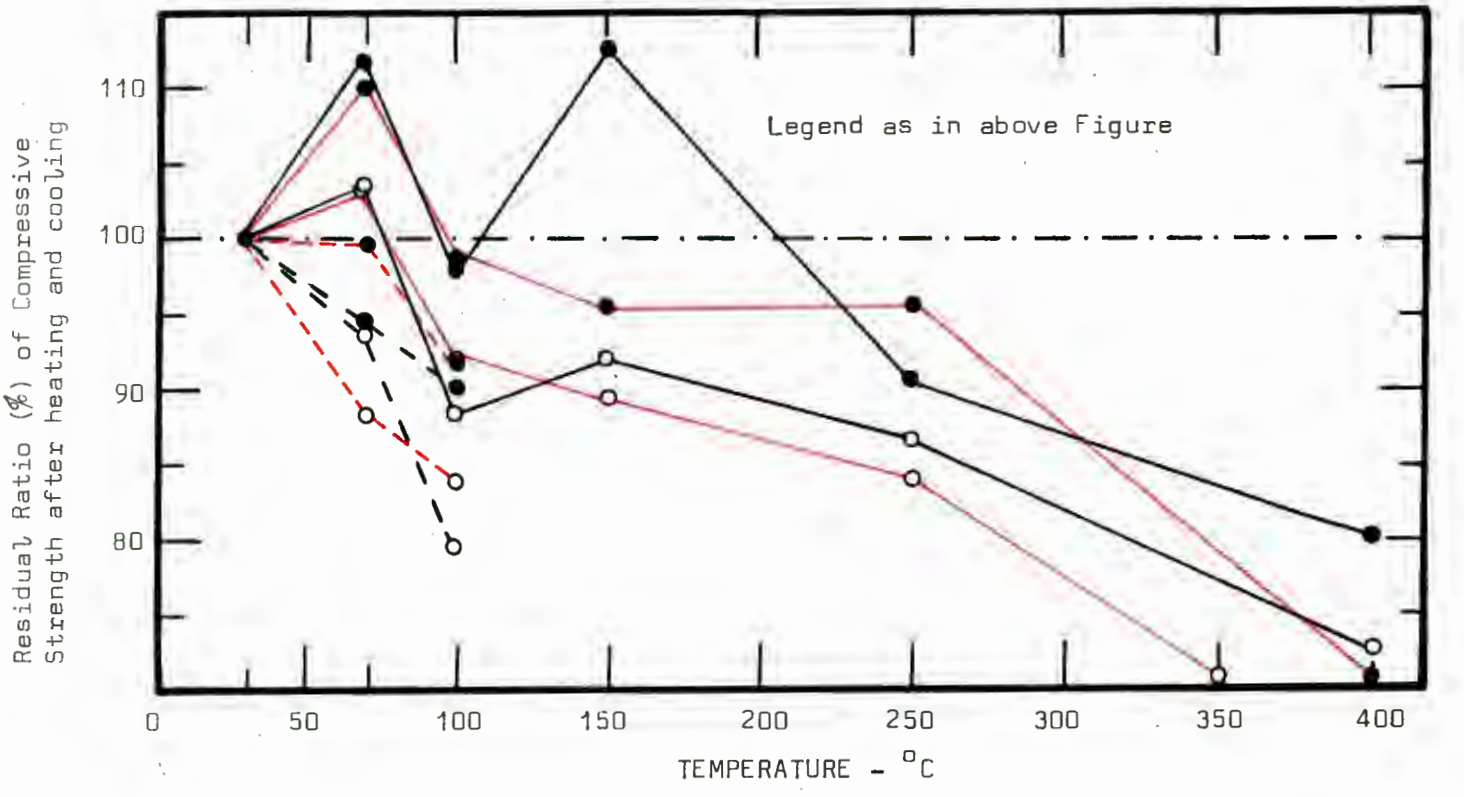


FIG.III.10: The residual ratio (%) of compressive strength for specimens tested after cooling : Mixes BCY and BMY.

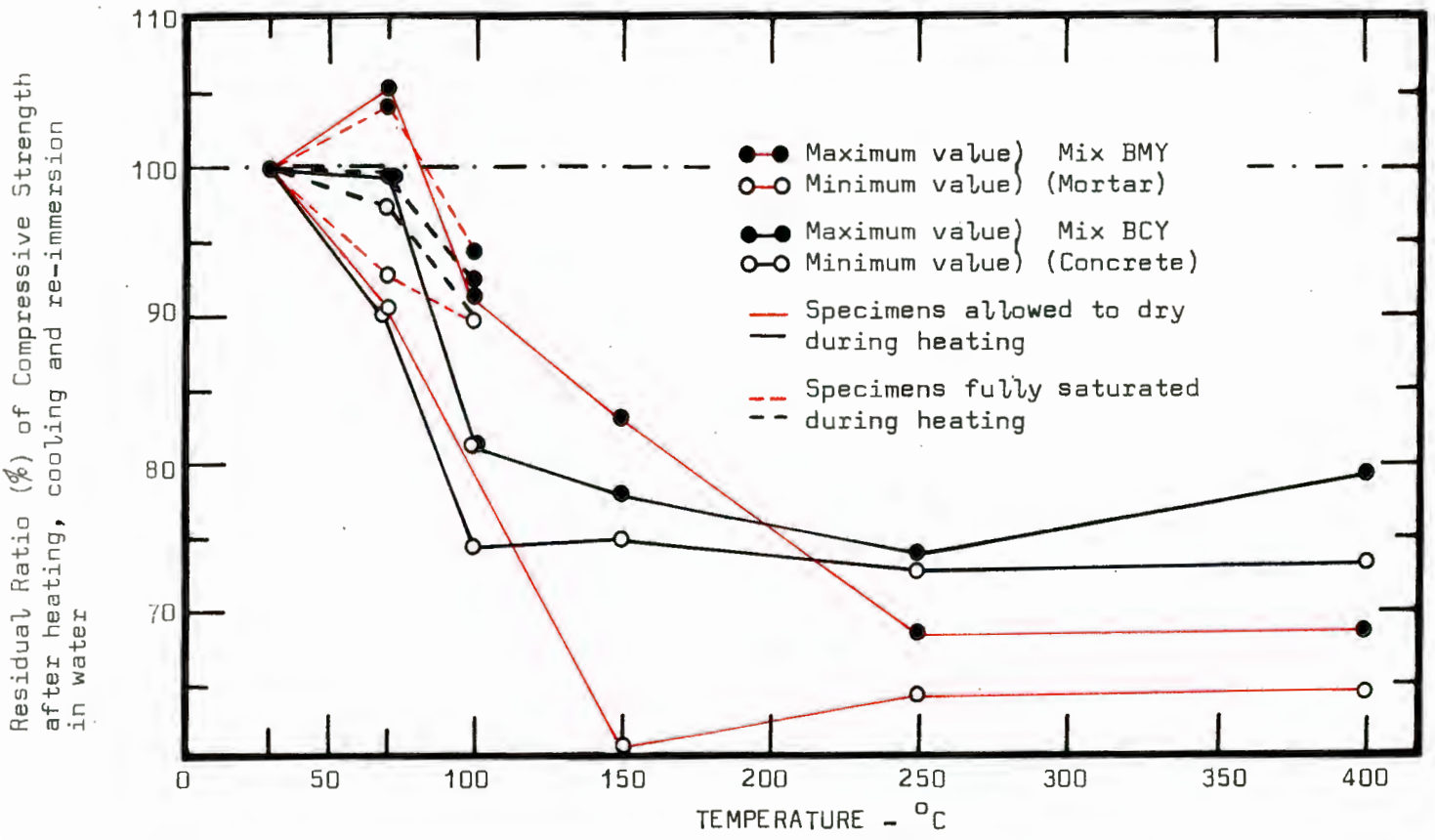


FIG.III.11: The residual ratio (%) of compressive strength for specimens tested after 1 week re-immersion in water : Mixes BCY and BMY.

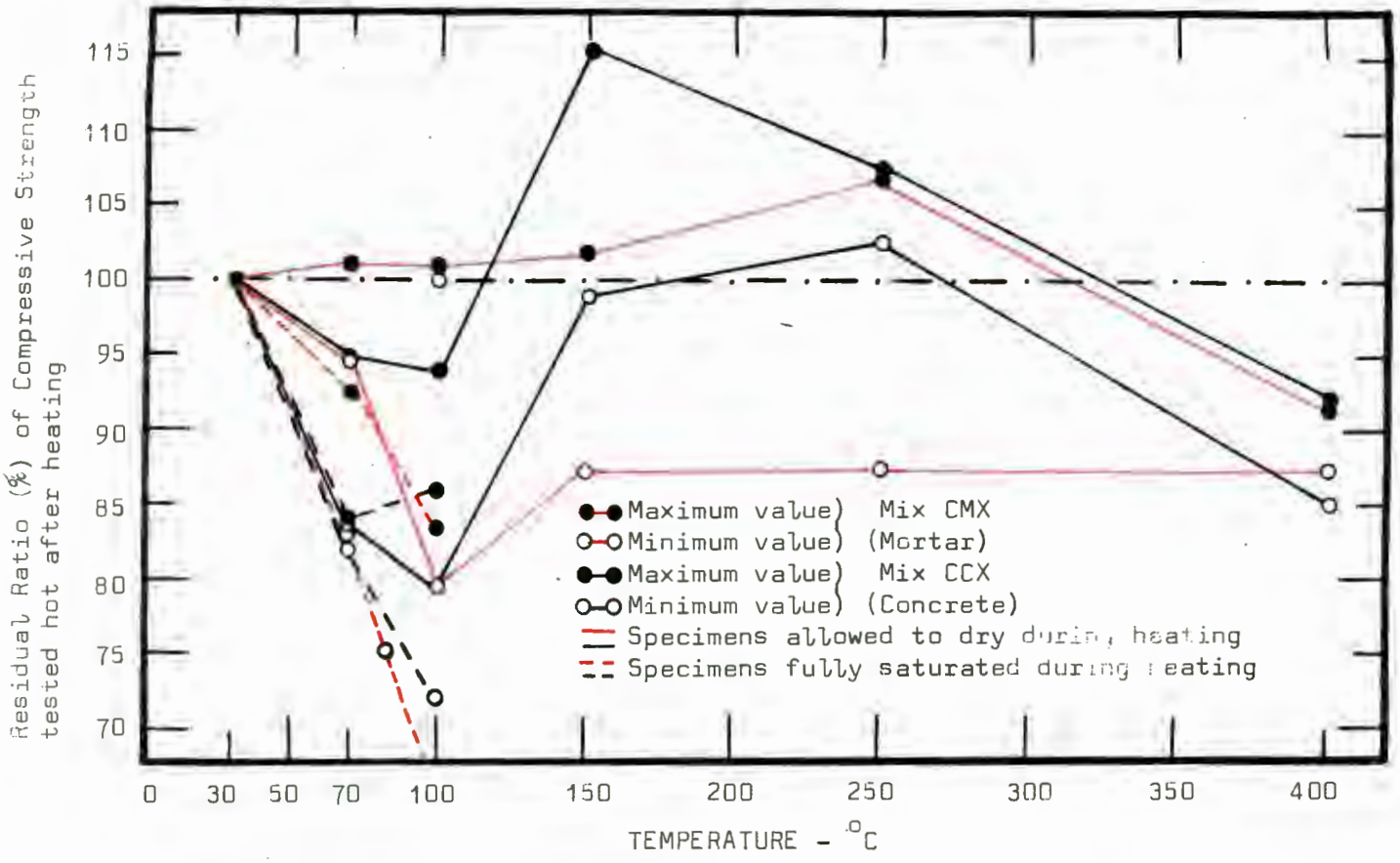


FIG.III.12: The residual ratio (%) of compressive strength for specimens tested whilst hot : Mixes CCX and CMX.

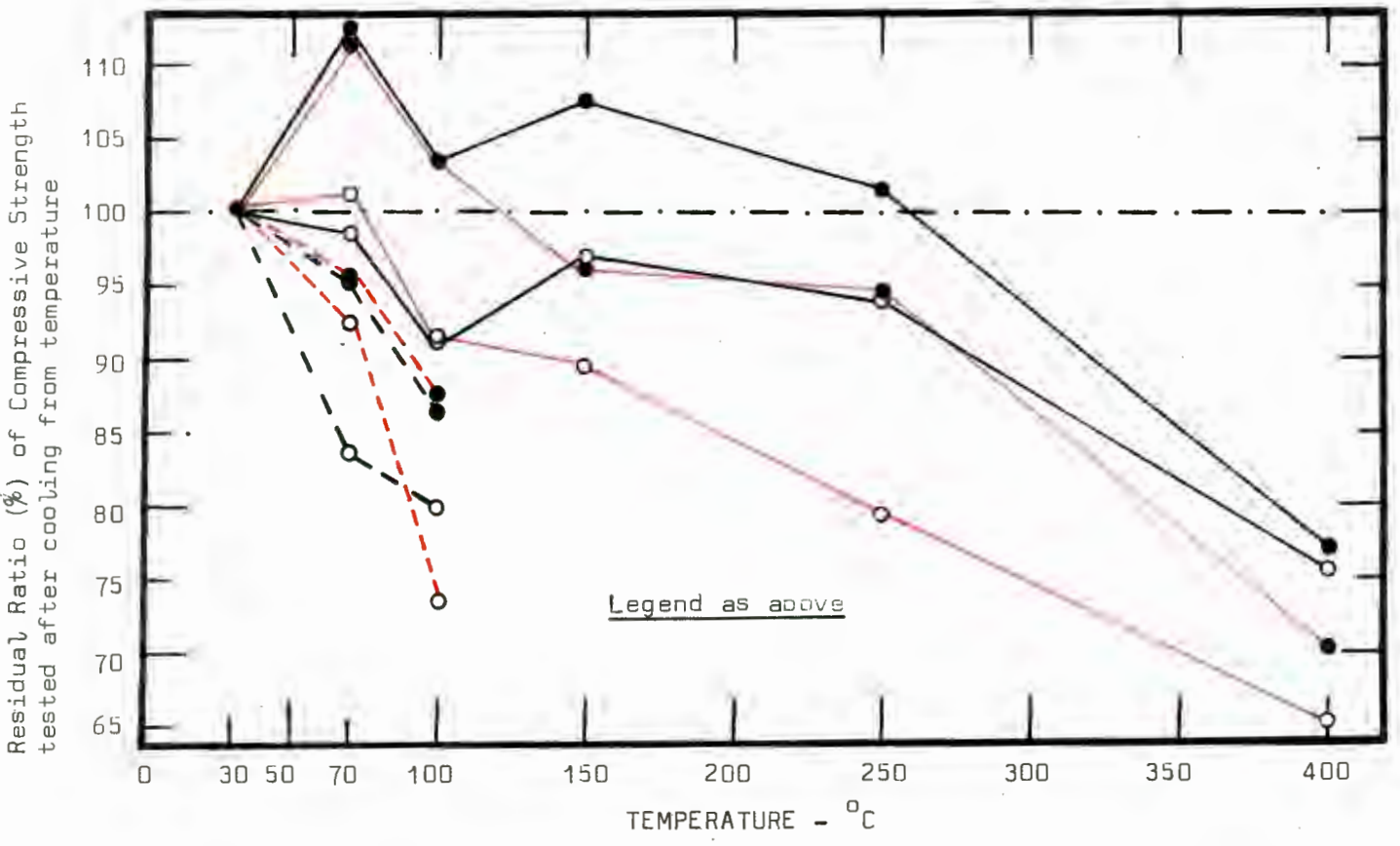


FIG.III.13: The residual ratio of compressive strength for specimens tested after cooling : Mixes CCX and CMX.

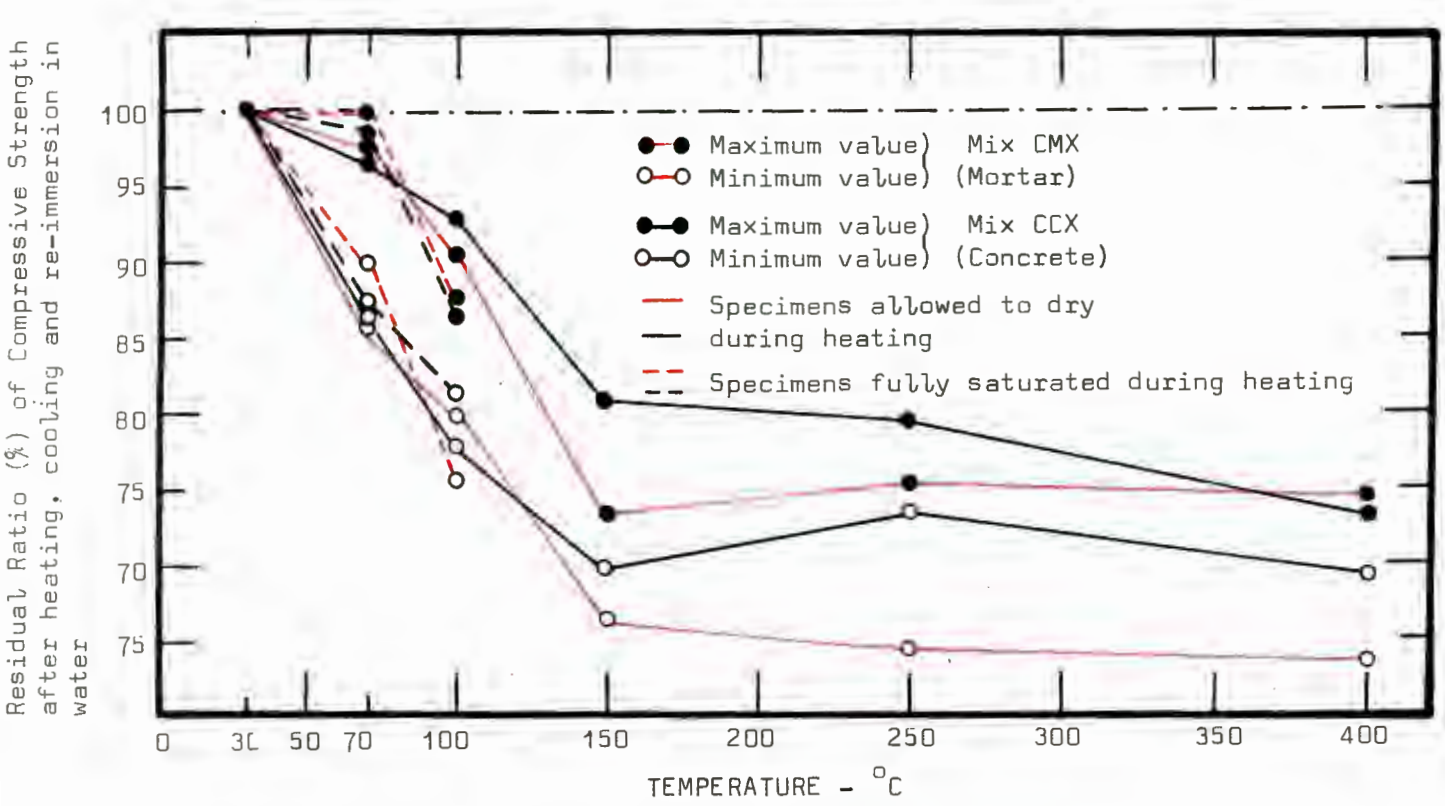


FIG.III.14: The residual ratio (%) of compressive strength for specimens tested after 1 week re-immersion in water : Mixes CCX and CMX.

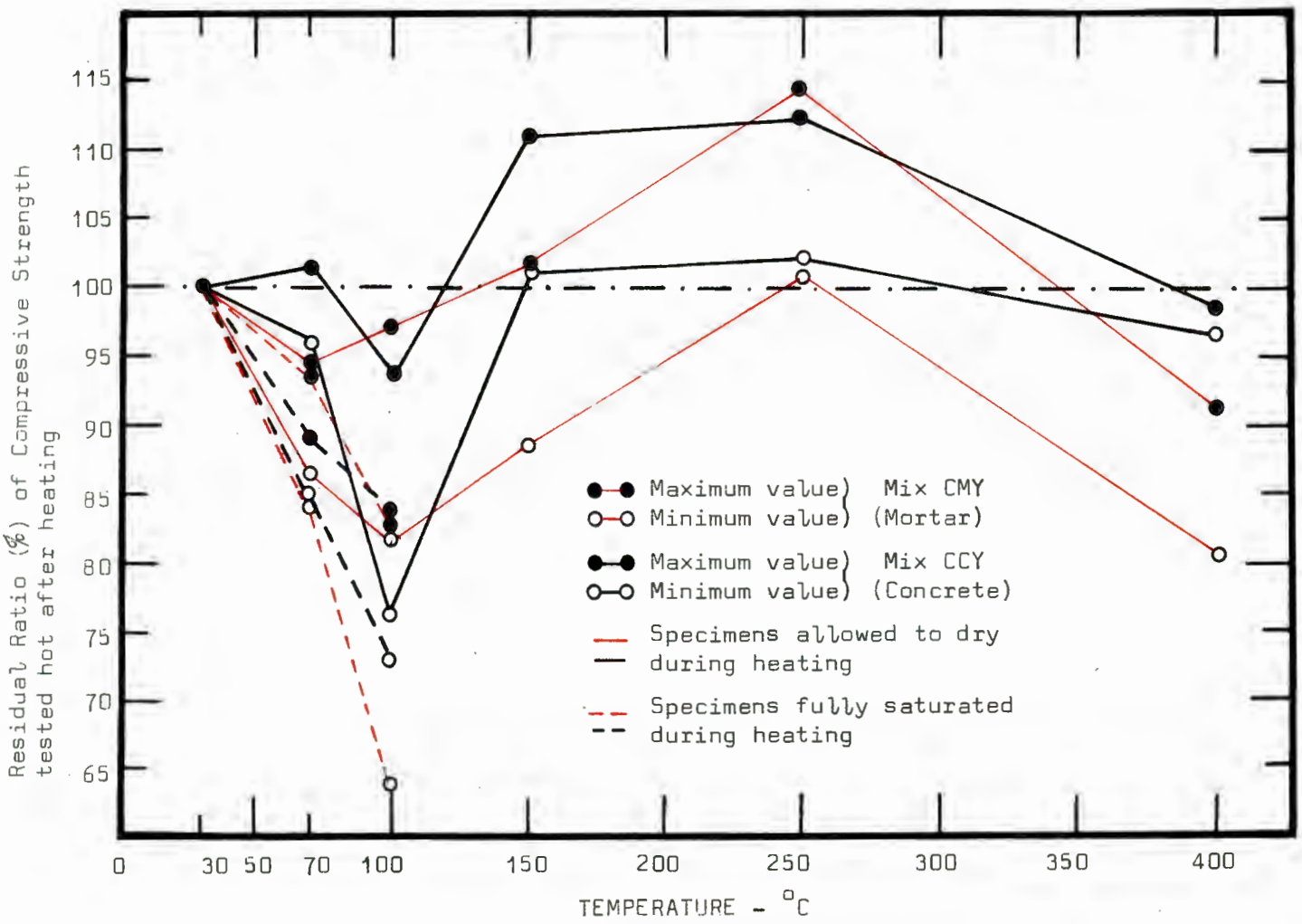


FIG.III.15: The residual ratio (%) of compressive strength for specimens tested whilst hot : Mixes CCY and CMY.

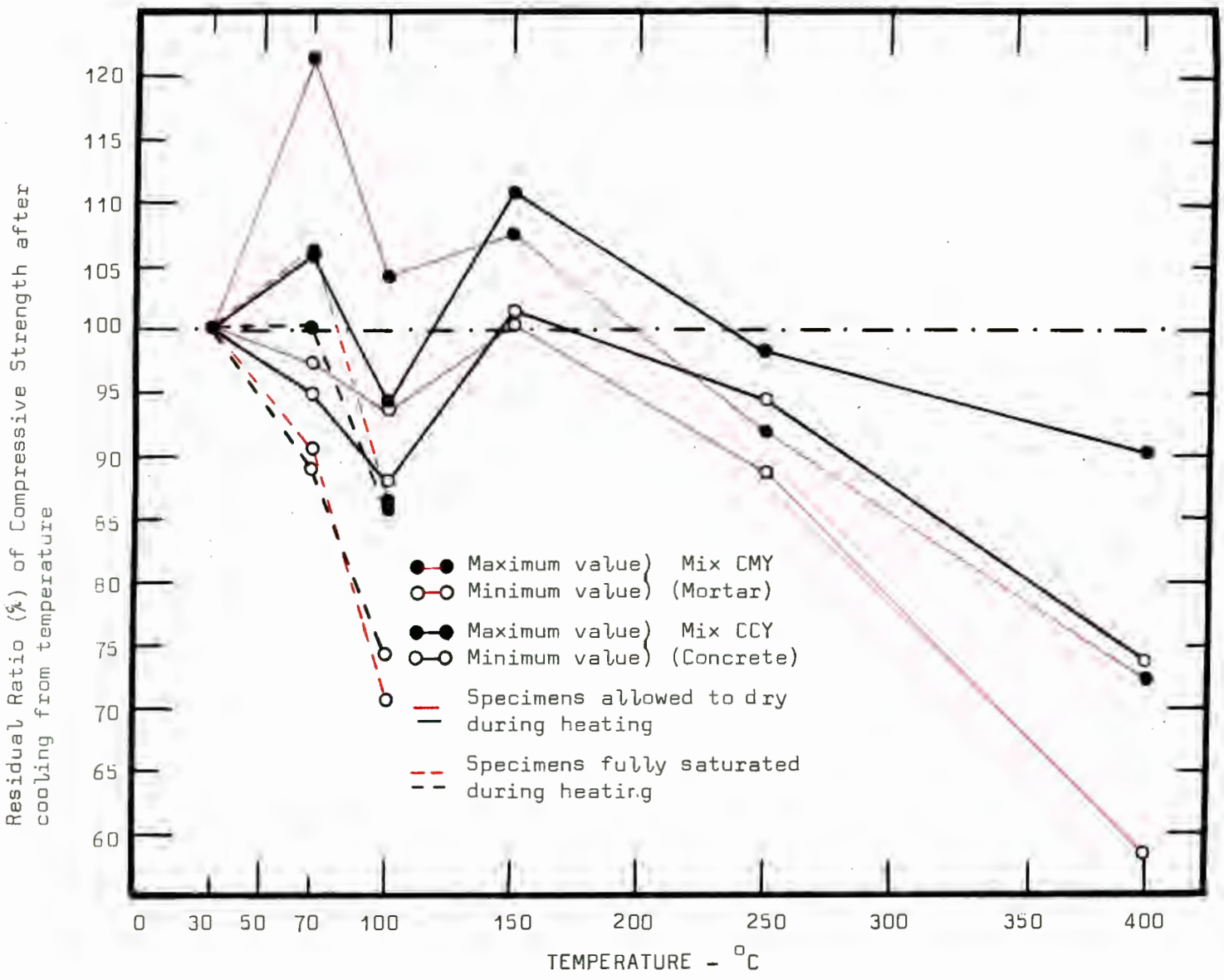


FIG.III.16: The residual ratio (%) of compressive strength for specimens tested after cooling : Mixes CCY and CMY.

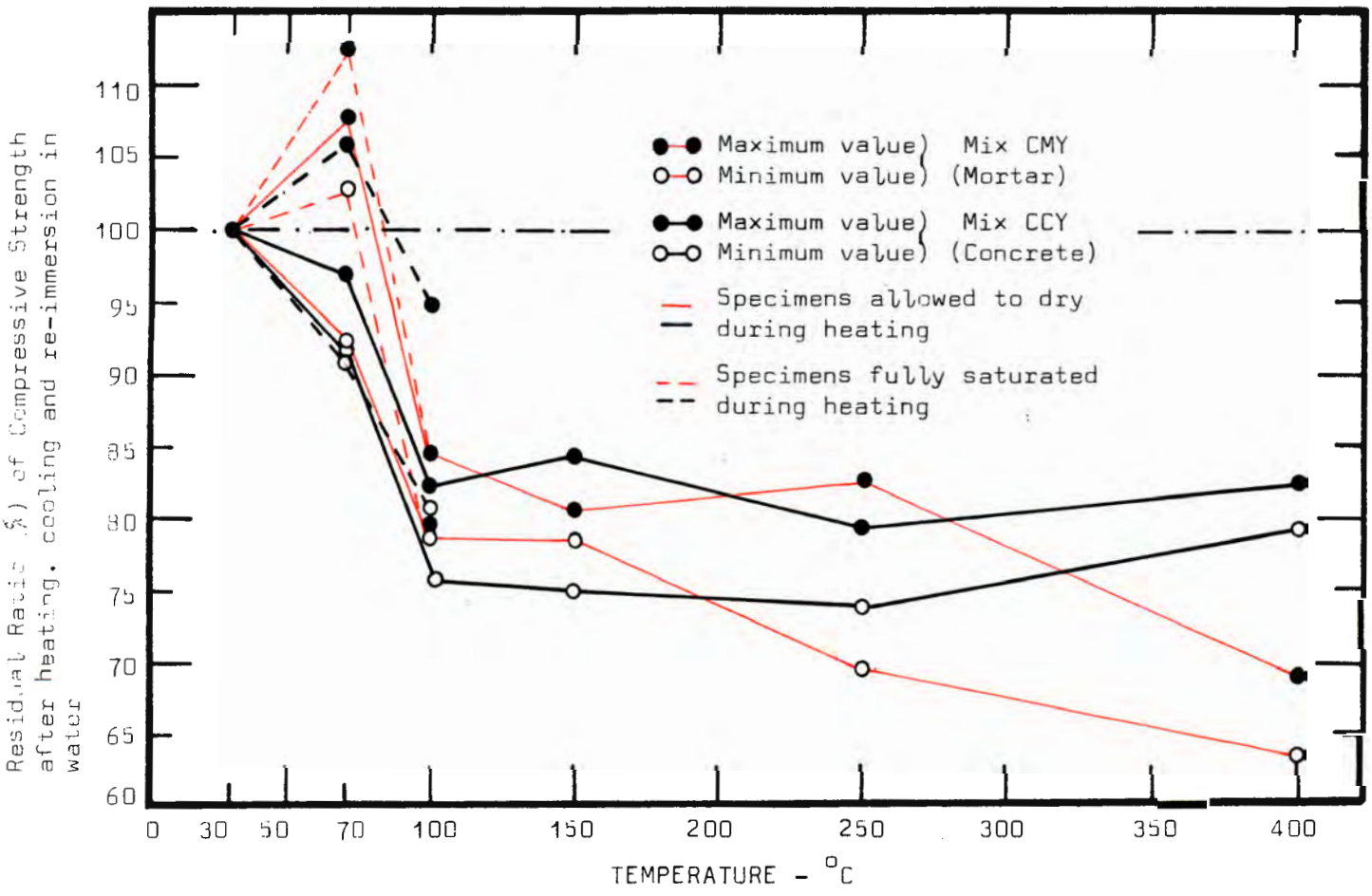


FIG.III.17: The residual ratio (%) of compressive strength for specimens tested after 1 week re-immersion in water : Mixes CCY and CMY.

2.1 The Compressive Strength of Concrete and Mortar Specimens. Tested whilst Hot.

From Figure III.9, Figure III.12 and Figure III.15 it is apparent that for test specimens which underwent drying during heating and were tested whilst hot:

(i) There is usually a large difference between the maximum residual ratio of compressive strength and the minimum residual ratio of compressive strength for the various concrete and mortar mixes, despite the fact that the tests were perfomred on specimens during the period when the test temperature remained constant. In some instances the difference between the maximum residual ratio of compressive strength and the minimum residual ratio of compressive strength is 30%. These differences are of sufficiently great magnitude to suggest that they were not caused by random variation between the test specimens.

(ii) Test specimens which were tested at a temperature level of 70°C usually exhibit a decrease in compressive strength. However, the reduction in compressive strength is never greater than approximately 15%.

(iii) Test specimens which were tested at 100°C usually exhibit a greater reduction in compressive strength than test specimens tested at 70°C, i.e. both the maximum residual ratio and the minimum residual ratio of compressive strength for specimens heated to 100°C are usually lower than the corresponding maxima and minima of specimens tested at 70°C. Values for the minimum residual ratio of between 75% and 80% were not uncommon.

(iv) Both the maximum and the minimum residual ratio of compressive strength for test specimens heated to 150°C are usually greater than the corresponding maximum and minimum residual ratios of specimens tested at either 70°C or 100°C. The minimum residual ratios of test specimens at 150°C are between 80% and 100%, and the maximum residual ratios of all the concrete and mortar mixes tested at 150°C are greater than 100%, i.e. the test specimens have compressive strength values which are higher than the mean compressive strength of the control specimens. The increase in compressive strength varied between 1% and 17% for the different concrete and mortar mixes.

(v) The minimum residual ratio of compressive strength for specimens tested at 250°C is usually greater than the minimum residual ratio for the corresponding specimens heated to either 70°C, 100°C or 150°C. Values for the minimum residual ratio were never smaller than 88%. The maximum residual ratio of compressive strength for test specimens heated to 250°C does not exhibit similar trends for the three pairs of concrete and mortar mixes, viz. the concrete mix BCY and corresponding mortar mix BMY exhibit values of compressive strength approximately 10% lower than the values at 150°C, whereas the concrete mix CCY and corresponding mortar mix CMY have up to 10% higher values for compressive strength at 250°C than at 150°C. The third pair of mixes (concrete mix CCX and mortar mix CMX) have maximum residual ratios which fall between the abovementioned two extreme cases. It is possible, though, that these comparatively small differences in the behaviour of the various mixes were caused by random variation between test specimens of a particular mix.

(vi) The compressive strength always decreases when test specimens are heated to 400°C. The residual ratio of compressive strength ranges between 80% and 98%, i.e. the reductions in compressive strength are approximately of the same order as the reductions in compressive strength that occurred at test temperatures of 70°C and 100°C. Furthermore, both the maximum and the minimum residual ratio of compressive strength for specimens tested at 400°C are always lower than the maximum and minimum residual ratios of corresponding specimens tested at 250°C.

Figure III.9, Figure III,12 and Figure III.15 show also the maximum and minimum residual ratio of compressive strength for test specimens which remained fully saturated during heating and were tested whilst hot. At test temperatures of both 70°C and 100°C the compressive strength of fully saturated specimens is always reduced. In some instances the reductions in compressive strength are as great as 20% at a test temperature of 70°C, and 36% at a test temperature of 100°C. It is apparent that at both 70°C and 100°C the reductions in compressive strength of specimens which remained fully saturated during heating are greater than the reductions in compressive strength which occurred for test specimens which underwent drying at these temperature levels.

It is particularly interesting in the abovementioned results that the specimens made from the various mortar mixes (each mortar mix corresponding to a particular concrete mix) underwent percentage reductions in compressive strength which were very similar to the percentage reductions exhibited by the corresponding concrete test specimens. This occurred for both specimens which were allowed to dry during heating and specimens which remained fully saturated during heating.

2.2 The Compressive Strength of Concrete and Mortar Specimens Tested after Slow Cooling from the Various Temperature Levels.

The results of compressive strength tests performed on concrete and mortar test specimens after cooling from the various temperature levels are shown in Figure III.10, Figure III.13 and Figure III.16. Figure III.10 illustrates the maximum and the minimum residual ratios of compressive strength for mixes BCY and BMY, Figure III.13 the maximum and minimum residual ratios for mixes CCX and CMX, and Figure III.16 the data for mixes CCY and CMY. The values shown in these diagrams refer to the maximum and the minimum residual ratio that was obtained for the test specimens during the period when the temperature remained constant, i.e. the residual ratio values which were measured on specimens subjected to temperature cycling are not considered at present.

The data for specimens which were allowed to dry during heating as well as for specimens which remained fully saturated during heating are shown in the abovementioned diagrams.

From Figure III.10, Figure III.13 and Figure III.16 it is apparent that for both specimens which remained fully saturated during heating and specimens which were allowed to dry during heating, there are usually comparatively large differences between the maximum residual ratio and the minimum residual ratio of compressive strength. In some instances the difference between the maximum and minimum residual ratio is 20%, although it is usually of the order of 10%. The latter of these differences could have been caused by the random variation of compressive strength between test specimens; the former value, however, suggests that at certain temperature levels the compressive strength underwent a change during the heating period.

Figure III.10, Figure III.13 and Figure III.16 indicate that for specimens which were allowed to dry during heating:

(i) Both the maximum and the minimum residual ratios of compressive strength determined on specimens cooled from 70°C before testing are always higher than the respective maximum and minimum residual ratios of compressive strength for specimens tested at 70°C whilst hot. Furthermore, test specimens which were cooled from 70°C before testing usually have residual ratios of compressive strength greater than 100%, i.e. the compressive strength is higher than the mean compressive strength of the control specimens. The largest increase in compressive strength was 20%, but increases of approximately 10% were more usual.

(ii) Both the maximum and the minimum residual ratios of compressive strength for specimens cooled from 100°C before testing were usually between 5% and 10% higher than the respective maximum and minimum residual ratios of compressive strength for specimens tested at 100°C whilst hot. In general, values of the residual ratio range between 90% and 105%, the residual ratio of compressive strength for specimens tested after cooling from 100°C being always lower than the corresponding residual ratio for specimens tested after cooling from 70°C.

(iii) The residual ratios of compressive strength for specimens cooled from 150°C before testing are either higher than or approximately the same as the corresponding residual ratios of specimens tested after cooling from 100°C. Values of the residual ratio range between 90% and 110%. Comparing the residual ratios of compressive strength for specimens tested whilst hot at 150°C (Figure III.9, Figure III.12 and Figure III.15) to the residual ratios for specimens which were cooled from 150°C before testing (Figure III.10, Figure III.13 and Figure III.16), it is not possible to discern any trend as regards differences in compressive strength arising from these two test conditions.

(iv) Both the maximum and the minimum residual ratios of compressive strength for specimens tested after cooling from 250°C are always lower than the corresponding maximum and minimum residual ratios of specimens cooled from either 70°C, 100°C or 150°C before testing. Values of the residual ratio of compressive strength range from

80% to 101%. However, the values usually fall between 85% and 95%. It is particularly interesting that these residual ratios are between 5% and 10% lower than the corresponding results for specimens tested whilst hot at 250°C.

(v) The residual ratios of compressive strength for specimens tested after cooling from 400°C are lower than the residual ratios for test specimens cooled from either 70°C, 100°C, 150°C or 250°C. Values of the residual ratio usually range between 70% and 80%, although in some instances values as low as 60% were obtained. These residual ratio values are always from 10% to 20% lower than the corresponding residual ratios for specimens tested whilst hot at a test temperature of 400°C.

The residual ratios of compressive strength for test specimens which remained fully saturated during heating and were cooled before testing indicate that:

(i) The maximum residual ratios and the minimum residual ratios of compressive strength for saturated specimens cooled from 70°C before testing are lower than the respective maximum and minimum residual ratios for specimens which underwent drying at 70°C and were cooled before testing. Values of the residual ratio are between 90% and 105%. These residual ratios are from 5% to 10% higher than the residual ratios for specimens which remained fully saturated at 70°C and were tested whilst hot.

(ii) The residual ratios of compressive strength for saturated specimens which were cooled from 100°C before testing are usually between 70% and 90%. The reductions in the compressive strength are;

(a) always larger than the reductions in compressive strength of saturated test specimens cooled from 70°C before testing, and

(b) from 5% to 15% greater than the reductions in compressive strength of test specimens which underwent drying at 100°C and were cooled before testing.

However,saturated specimens which were allowed to cool from 100°C before testing had residual ratios which were up to 13% greater than the corresponding residual ratios of saturated specimens heated to 100°C and tested whilst hot.

It is apparent from the results illustrated in Figure III.10, Figure III.13 and Figure III.16 that the maximum residual ratios as well as the minimum residual ratios of compressive strength for the various concrete mixes which underwent drying are usually higher than the respective maximum and minimum residual ratios of compressive strength for the corresponding mortar mixes. This is particularly noticeable for test specimens which underwent drying at temperatures of 250°C and 400°C; in some instances the mortar test specimens exhibit up to 16% greater reduction in compressive strength than the concrete specimens. The test specimens which remained fully saturated during heating do not indicate any trend in this regard.

2.3 The Compressive Strength of Test Specimens which were Cooled and Immersed in Water for 7 Days before Testing.

The maximum and minimum residual ratios of compressive strength for specimens which were stored in water for 7 days after slow cooling from the various temperature levels are illustrated in Figure III.11 (mixes BCY and BMY), Figure III.14 (mixes CCX and CMX) and Figure III.17 (mixes CCY and CMY). Each diagram shows the maximum residual ratios and the minimum residual ratios that were determined from tests on specimens which were removed from the furnace (waterbath) during the period when the temperature remained constant, i.e. the residual ratios obtained from specimens subjected to temperature cycling are not considered at present. The results for test specimens which underwent drying during heating indicate that:

(i) The residual ratios of compressive strength for test specimens heated to 70°C range between 85% and 105%. These results fall in the same range as those of test specimens which were tested hot at 70°C, but are from 5% to 10% lower than the corresponding data for test specimens slowly cooled from 70°C before testing.

(ii) The maximum residual ratios and the minimum residual ratios of compressive strength for specimens re-immersed in water for 7 days after cooling from 100°C are always lower than the corresponding residual ratios of test specimens re-immersed in water after cooling from 70°C. Values of the residual ratio range between 75% and 95%. Both the maximum residual ratio and the minimum residual ratio for specimens re-immersed in water after cooling from 100°C are always lower than;

(a) the respective maximum and minimum residual ratios of compressive strength for specimens tested hot at 100°C, and

(b) the respective maximum and minimum residual ratios for specimens tested after cooling from 100°C.

The abovementioned differences between the residual ratios of test specimens were more prominent for (b) than for (a) and were of the order of 10% to 15%.

(iii) Test specimens which were re-immersed in water for 7 days after slow cooling from 150°C always exhibit reductions in compressive strength. The reductions in strength ranged from 15% to 40%. Both the maximum residual ratio and the minimum residual ratio of compressive strength are;

(a) usually lower than the corresponding maximum and minimum residual ratios of compressive strength for test specimens which were re-immersed in water after slow cooling from 100°C,

(b) always lower than the respective residual ratios of compressive strength for specimens tested whilst hot at 150°C, and

(c) always lower than the respective residual ratios of compressive strength for specimens tested after slow cooling from 150°C.

(iv) The residual ratios of compressive strength for specimens which were cooled from 250°C and immersed in water for 7 days prior to testing, range between 65% and 85%. It appears that these data are not significantly different from the results for test specimens cooled from 150°C and immersed in water for 7 days prior to testing. However, the residual ratios are lower than both;

(a) the residual ratios of compressive strength for specimens tested hot at 250°C (between 20% and 30% lower), and

(b) the residual ratios of test specimens which were cooled from 250°C prior to testing (15% to 20% lower).

(v) Test specimens which were cooled from 400°C and immersed in water for 7 days before testing, exhibit reduction in compressive strength of the same order as the reductions which occurred for test specimens which were cooled from either 150°C or 250°C and immersed in water for 7 days before testing. Values of the residual ratio range between 65% and 85%. These values are from 10% to 20% lower than the residual ratios of compressive strength for specimens tested hot at 400°C. However, these residual ratios do not differ appreciably from the residual ratios for test specimens which were tested immediately after cooling from 400°C.

The maximum residual ratios and the minimum residual ratios of compressive strength for saturated specimens which were cooled from temperatures of either 70°C or 100°C and immersed in water for 7 days before testing, are shown in Figure III.11, Figure III.14 and Figure III.17. These results indicate that:

(i) the residual ratios of compressive strength for test specimens cooled from 70°C are usually between 90% and 110%. These values are approximately the same as the residual ratios for;

(a) the corresponding test specimens which underwent drying at 70°C and were cooled and re-immersed in water for 7 days before testing, and

(b) the corresponding test specimens which remained fully saturated at 70°C and were cooled before testing.

(ii) For saturated test specimens cooled from 100°C and re-immersed in water for 7 days, the reductions in compressive strength are always greater (in some instances 20% greater) than the reductions which occurred for saturated test specimens cooled from 70°C and stored in water for 7 days before testing. Values of the residual ratios ranged from 75% to 95%. It appears that these reductions in compressive strength are not significantly different from either;

(a) the reduction in compressive strength which occurred for test specimens which underwent drying at 100°C and were cooled and immersed in water for 7 days before testing, or

(b) the reductions in compressive strength for saturated test specimens cooled from 100°C before testing.

In all the abovementioned results for the compressive strength of test specimens which were stored in water for 7 days before testing, it is again apparent that the concrete mixes exhibit percentage reductions in compressive strength which are approximately the same as those of the corresponding mortar mixes. The exception to this occurs at temperatures of 250°C and 400°C. At these temperature levels the mortar test specimens usually have lower residual ratios than the corresponding concrete test specimens. ie. greater reductions in compressive strength.

2.4 The Compressive Strength of Test Specimens which were Subjected to Temperature Cycling

The residual ratios of compressive strength for test specimens which were subjected to temperature cycling are shown in Figure III.18 to Figure III.26. For each of these figure the maximum and minimum residual ratios that are illustrated were chosen from the three respective compressive strength tests carried out;

(i) at the end of the heating period during which the test temperature remained constant,

(ii) at the end of the first cooling/re-heating cycle, and

(iii) at the end of the second cooling/re-heating cycle.

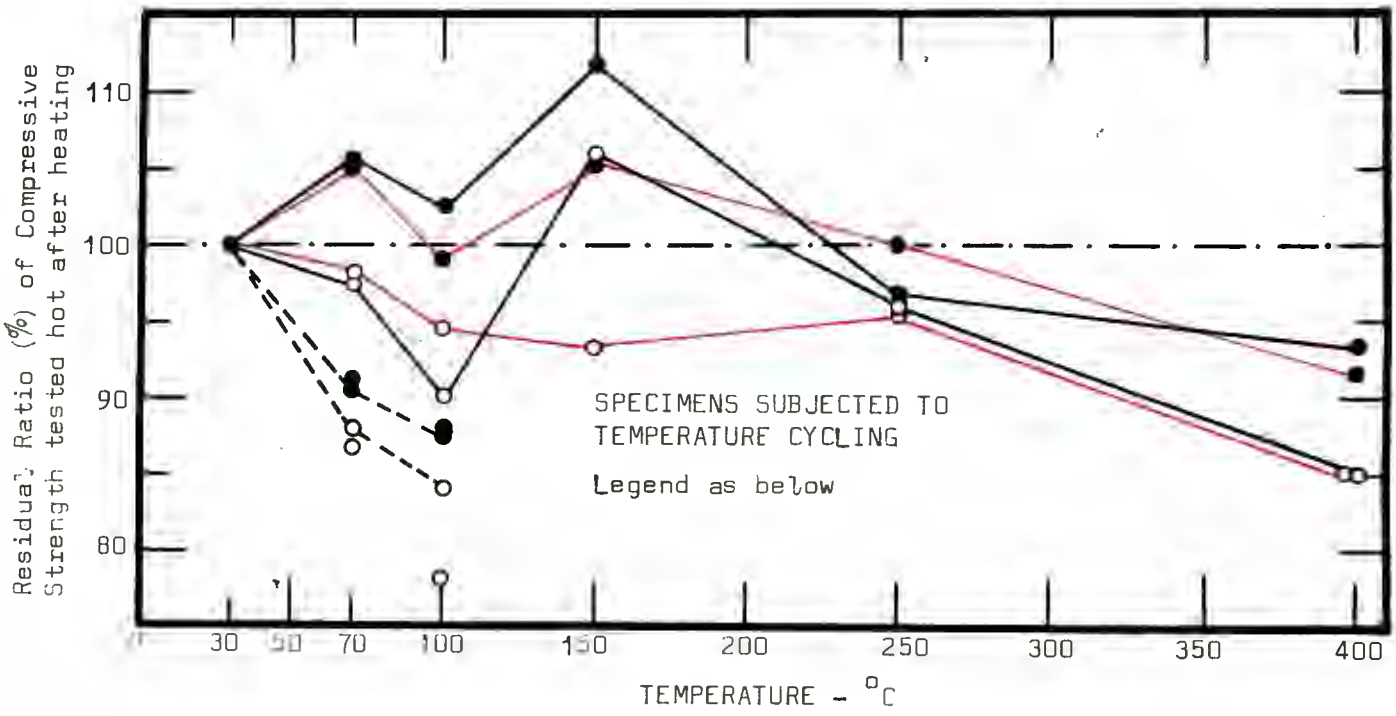


FIG.III.18: The residual ratio (%) of compressive strength for specimens tested whilst hot : Mixes BCY and BMY.

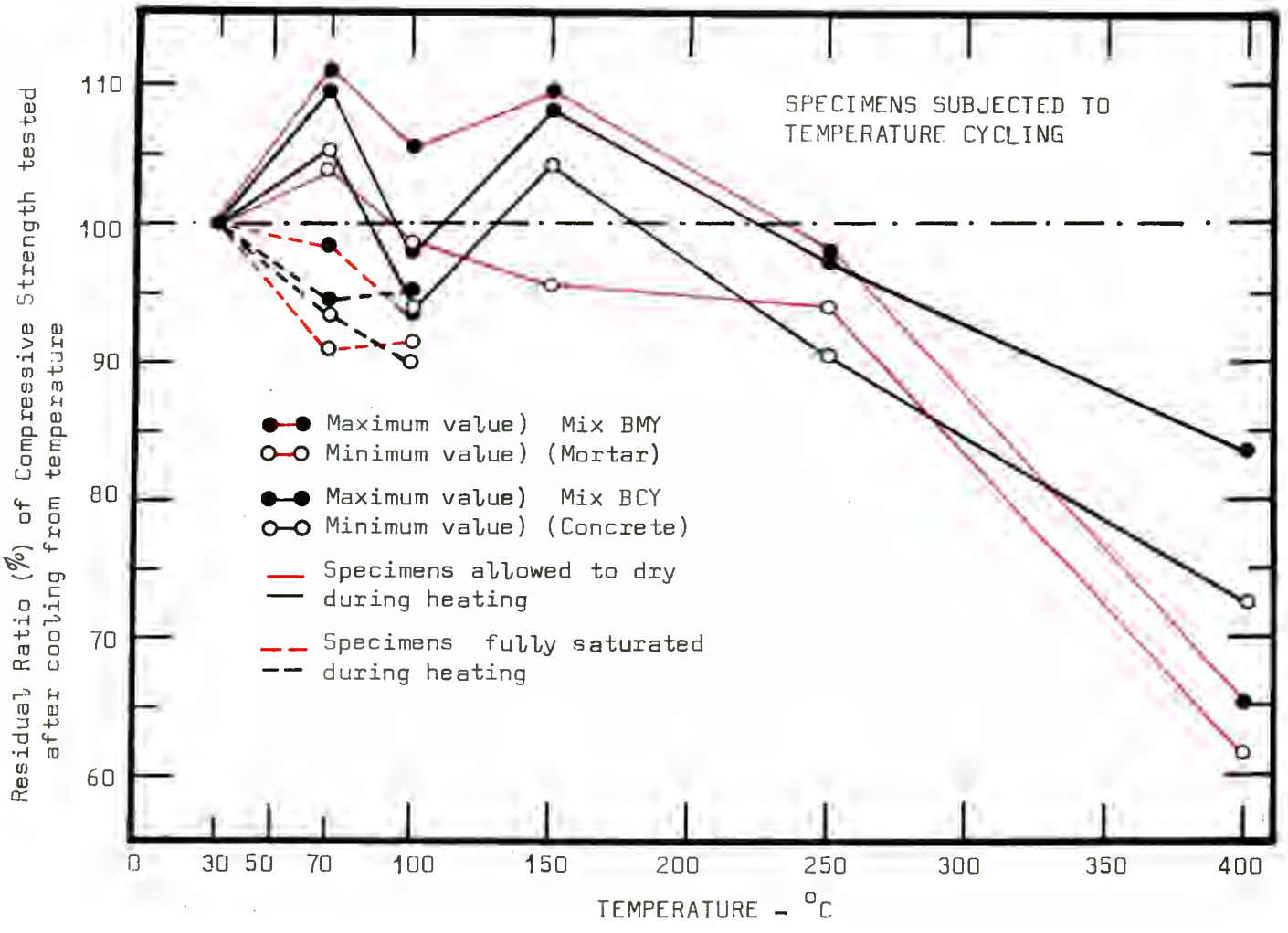


FIG.III.19: The residual ratio (%) of compressive strength for specimens tested after cooling : Mixes BCY and BMY.

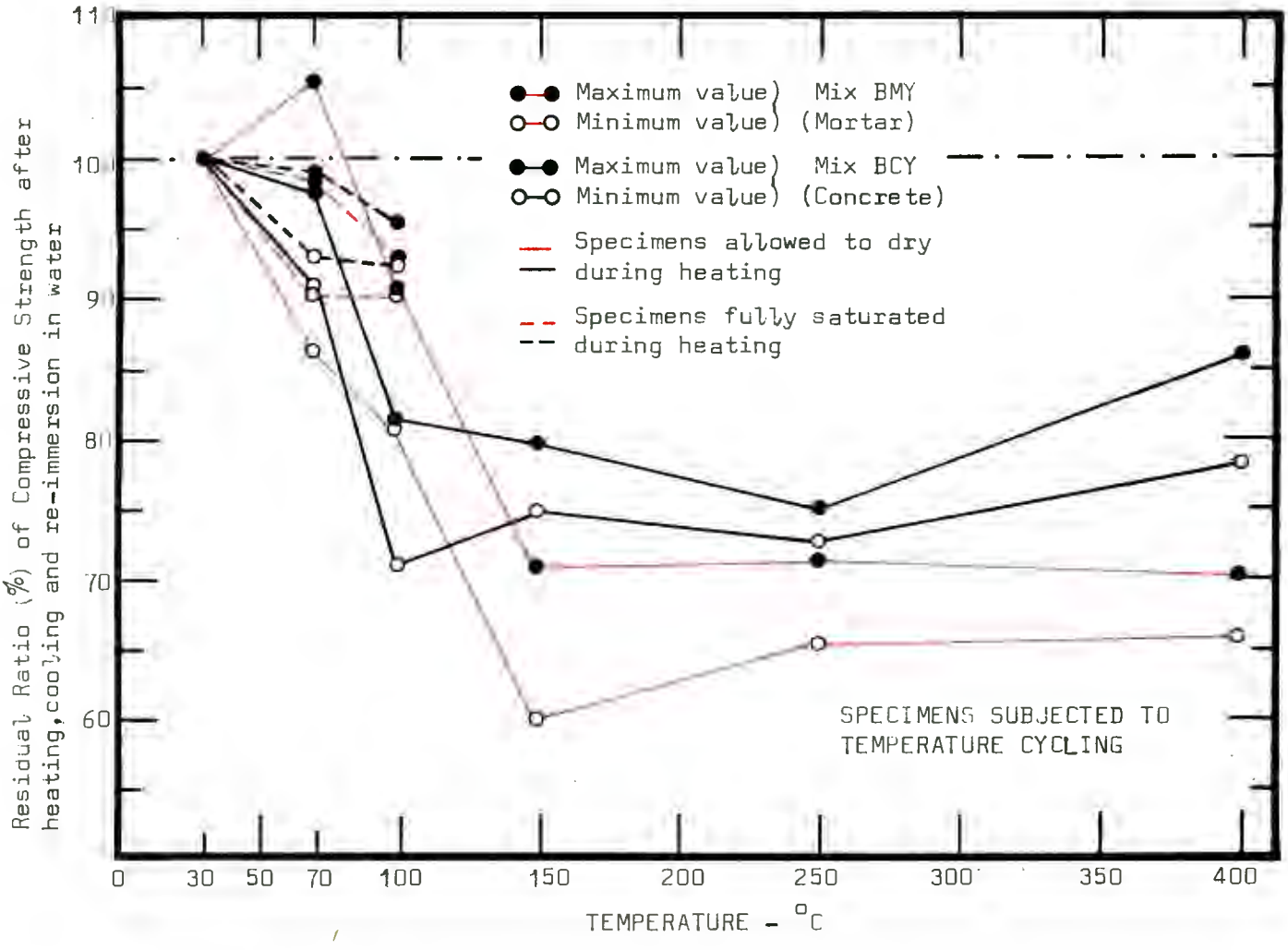


FIG.III.20: The residual ratio (%) of compressive strength of specimens tested after 1 week re-immersion in water : Mixes BCY and BMY.

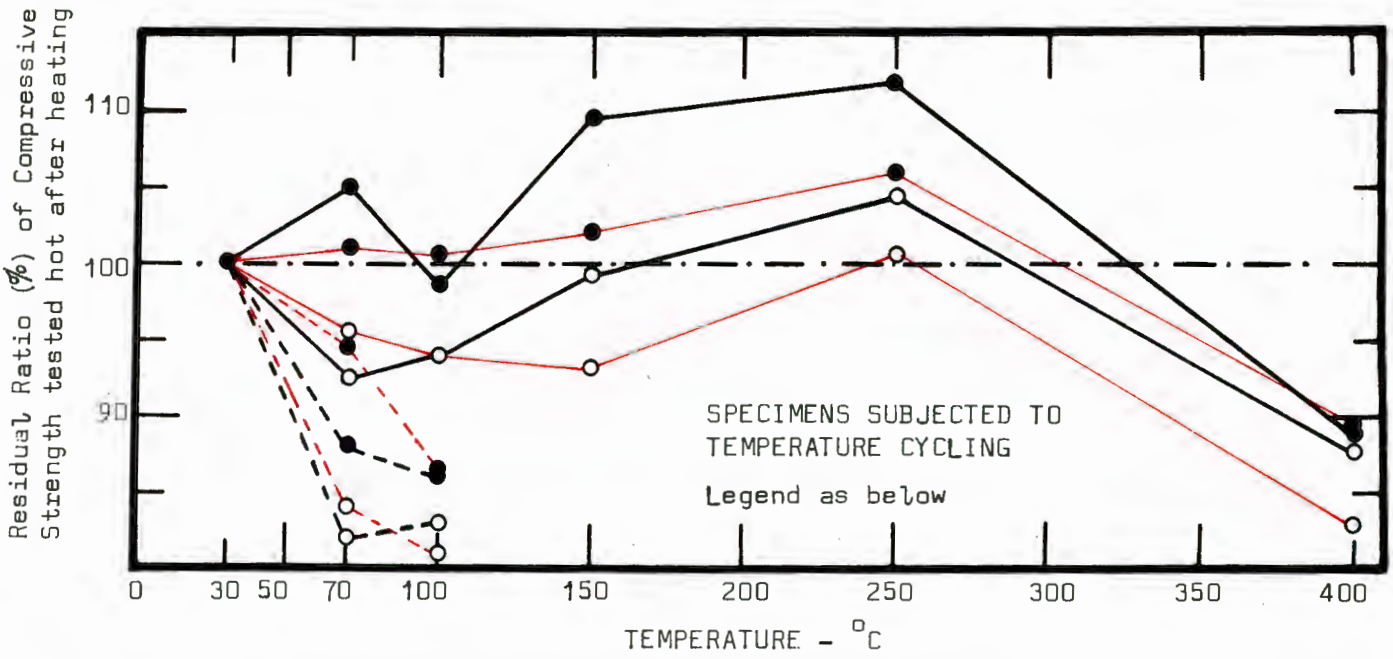


FIG.III.21: The residual ratio (%) of compressive strength for specimens tested whilst hot : Mixes CCX and CMX.

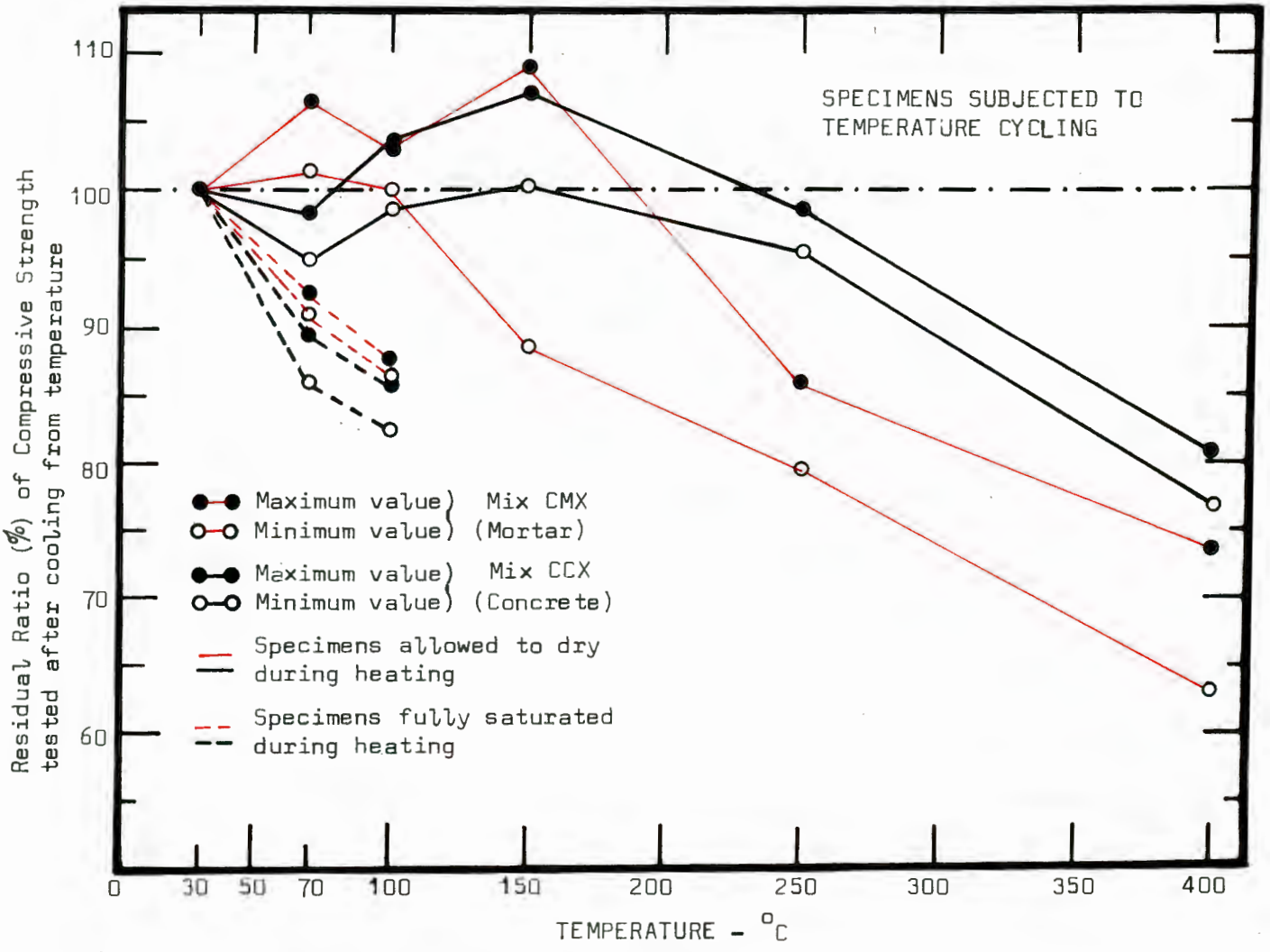


FIG.III.22: The residual ratio (%) of compressive strength for specimens tested after cooling : Mixes CCX and CMX.

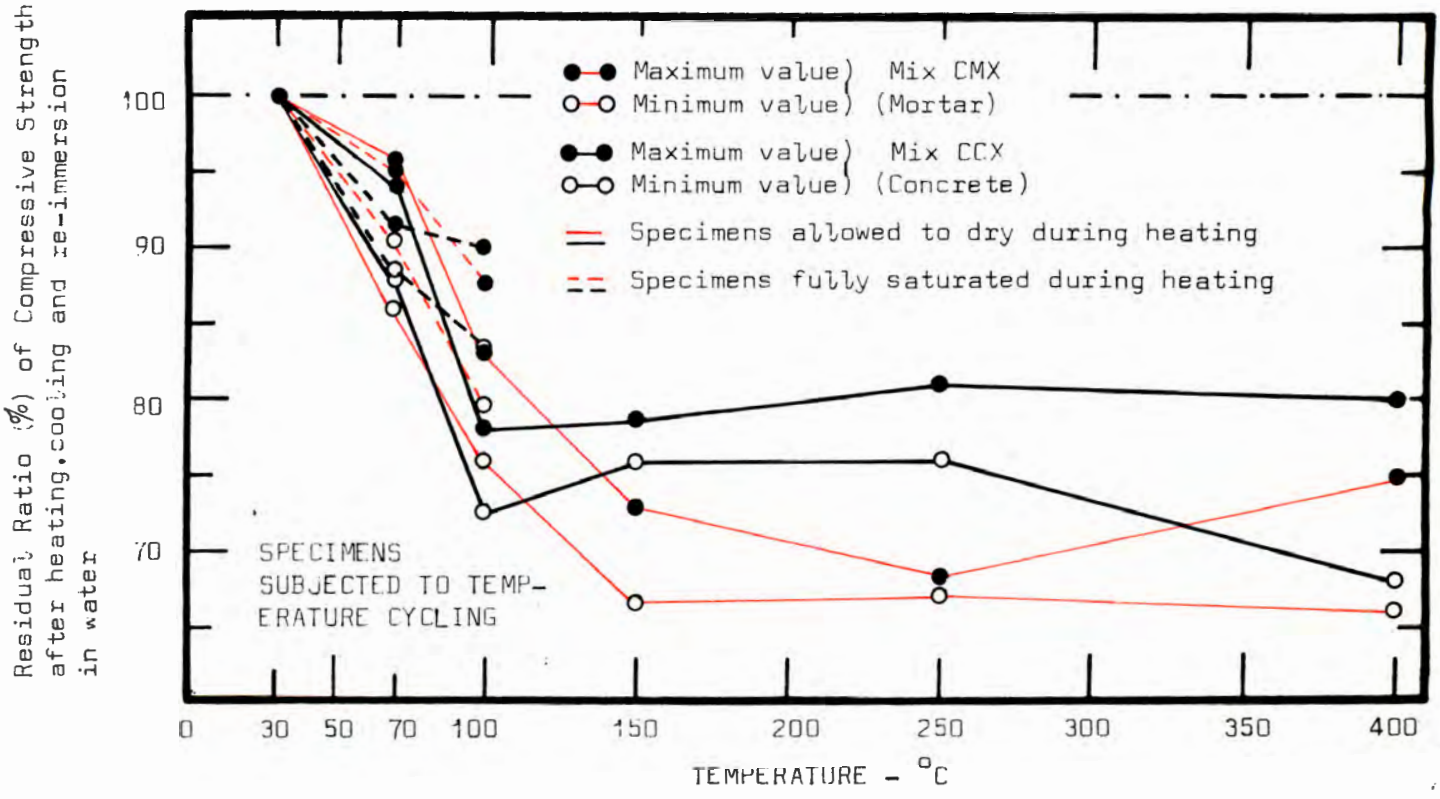


FIG.III.23: The residual ratio (%) of compressive strength for specimens tested after 1 week re-immersion in water : Mixes CCX and CMX.

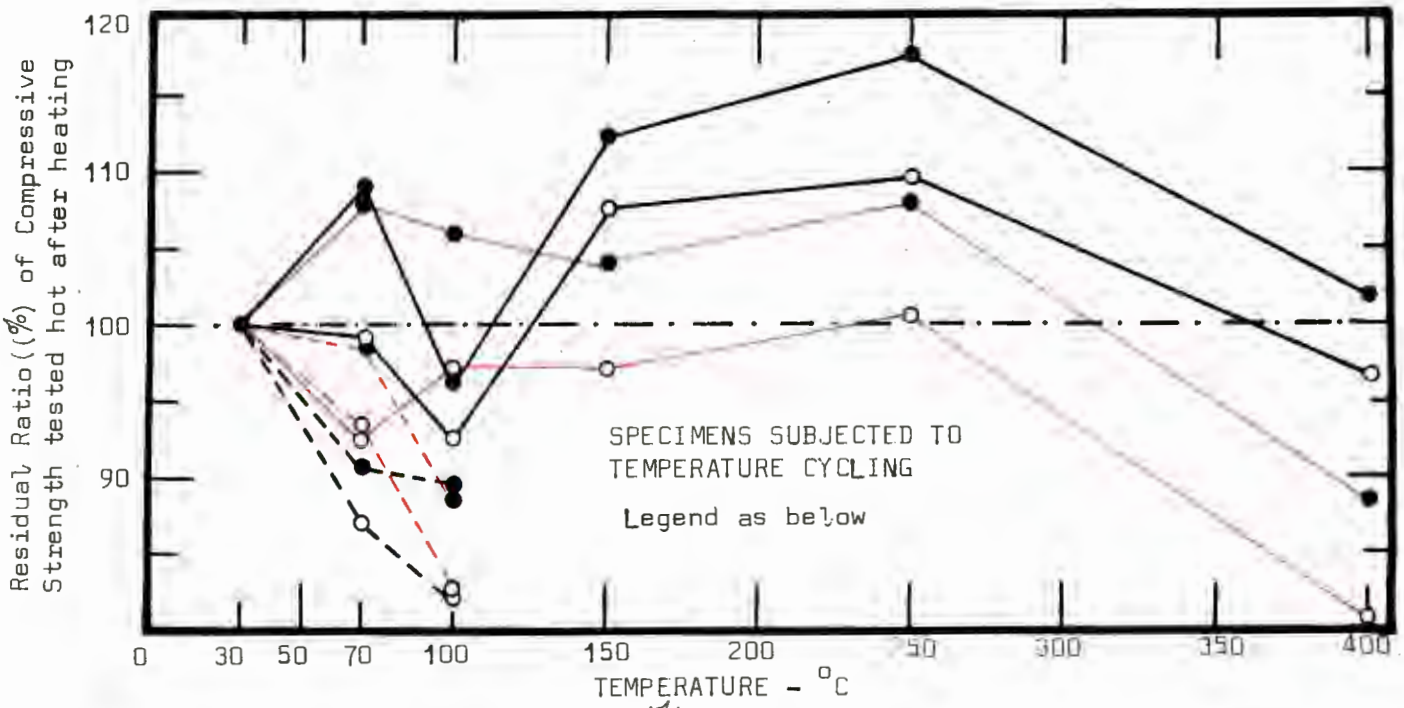


FIG.III.24: The residual ratio (%) of compressive strength for specimens tested whilst hot : Mixes CCY and CMY.

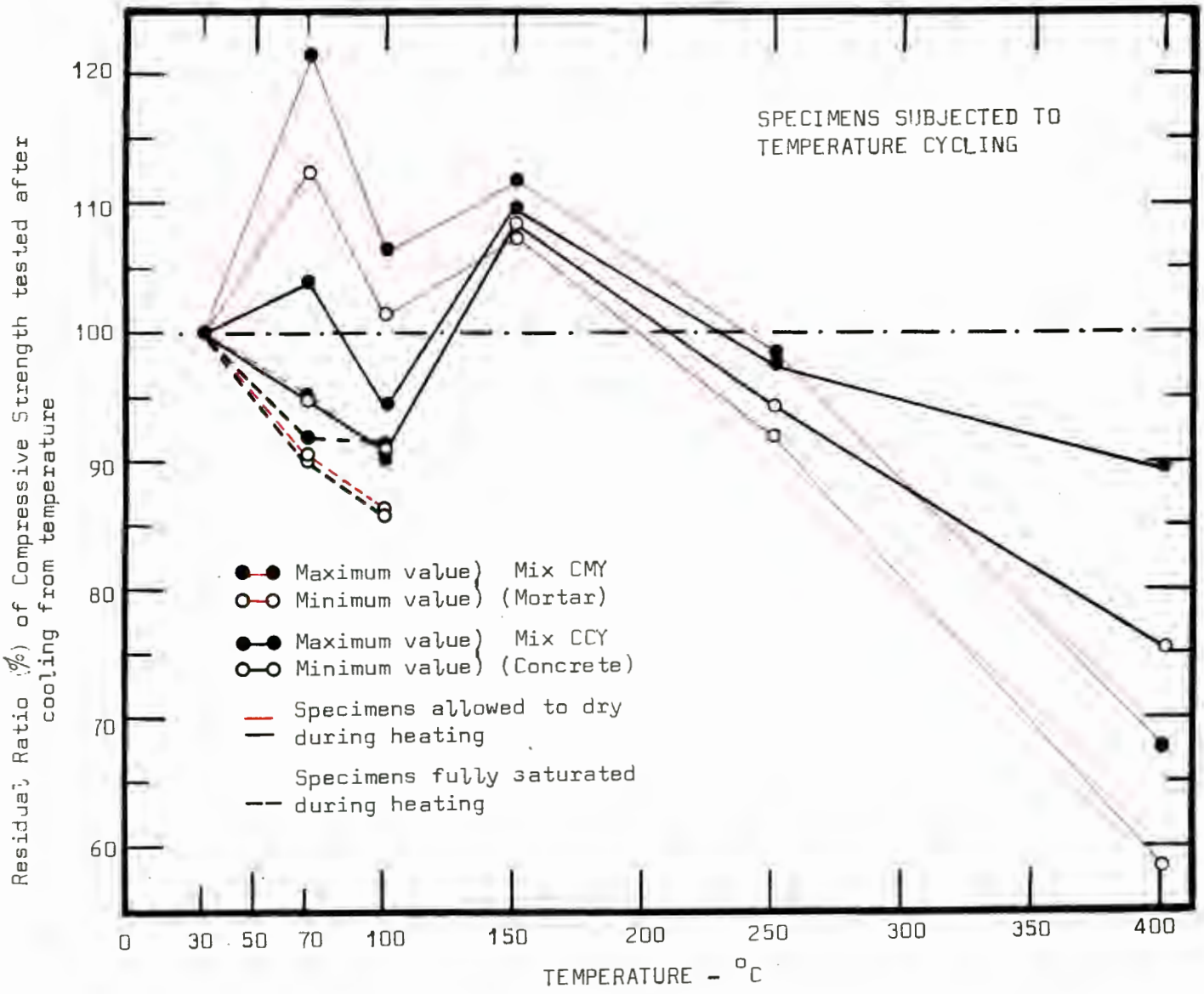


FIG.III.25: The residual ratio (%) of compressive strength for specimens tested after cooling : Mixes CCY and CMY.

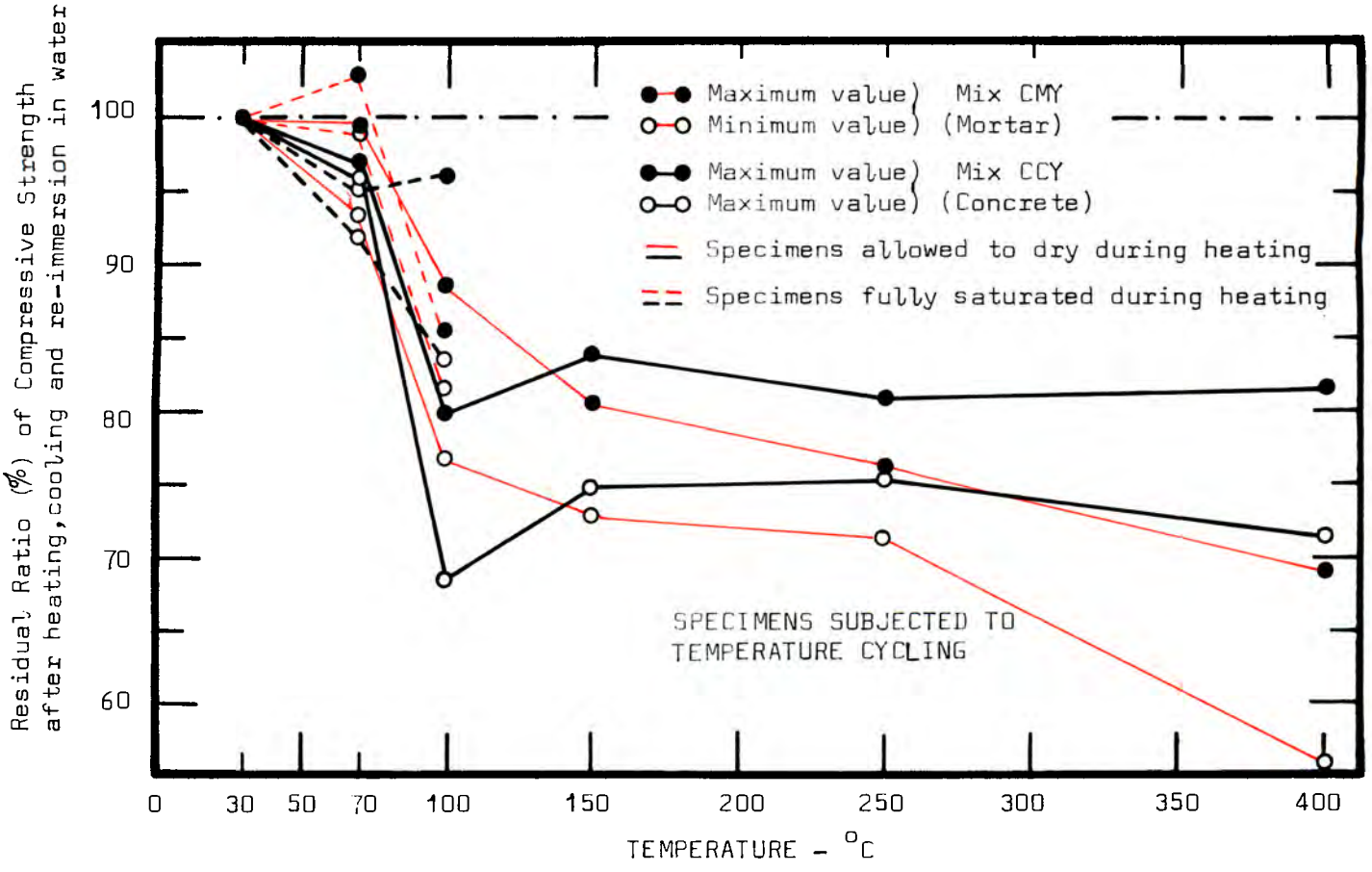


FIG.III.26: The residual ratio (%) of compressive strength for specimens tested after 1 week re-immersion in water : Mixes CCY and CMY.

The maximum and the minimum residual ratios of compressive strength for the concrete mix BCY and the corresponding mortar mix BMY are illustrated in Figure III.18, Figure III.19 and Figure III.20 for the following respective test cases;

(i) specimens tested whilst hot,

(ii) specimens were cooled before testing, and

(iii) specimens were cooled from the test temperature and immersed in water for 7 days before testing.

The residual ratios of compressive strength for the concrete mix CCX and the corresponding mortar mix CMX are shown in Figure III.21, Figure III.22 and Figure III.23 for the abovementioned respective test cases. Figure III.24 Figure III.25 and Figure III.26 illustrate the residual ratios for mixes CCY and CMY.

In all the abovementioned diagrams the data for both specimens which underwent drying during heating and specimens which remained fully saturated during heating are shown. For test specimens which were allowed to dry during heating, Figure III.18 to Figure III.26 indicate that:

(i) The difference between the maximum and the minimum residual ratio of compressive strength for test specimens of a particular mix is usually less than 10%. Consequently, it appears that in most instances the effect of temperature cycling was not significant since differences of this order could have resulted from the random variation of compressive strength between different test specimens of a particular mix.

(ii) For test specimens which were tested whilst hot at temperatures of either 70°C, 100°C or 150°C, both the maximum and the minimum residual ratios of compressive strength are usually greater than the corresponding maximum and minimum residual ratios of test specimens which were not subjected to temperature cycling. In some instances the difference between the minimum residual ratios of compressive strength (referring to the above two test cases) is as large as 15%, but the difference is usually not greater than 5%. Test specimens which were tested whilst hot at temperatures of either 250°C or 400°C exhibit residual ratios of compressive strength which are approximately the same as the residual ratios for specimens which were

heated to these temperature levels but not subjected to temperature cycling.

(iii) For test specimens which were tested after slow cooling from temperatures of either 70°C, 100°C, 150°C, 250°C or 400°C the residual ratios of compressive strength are approximately the same as the residual ratios for the corresponding test specimens which were not subjected to temperature cycling. Also, it appears that for test specimens which underwent temperature cycling there is little difference between the residual ratios of compressive strength for specimens tested hot at either 70°C, 100°C or 150°C and the corresponding residual ratios of compressive strength for test specimens cooled from these temperature levels before testing. However, for test temperatures of either 250°C or 400°C, greater reductions in compressive strength occurred for specimens tested after cooling than for specimens tested whilst hot; the additional reduction in compressive strength which occurred for specimens which were heated to 400°C was in some instances 25%.

(iv) The residual ratios of compressive strength for test specimens cooled from temperatures of either 70°C, 100°C, 150°C, 250°C or 400°C and immersed in water for 7 days before testing, are almost exactly similar to the residual ratios for the corresponding specimens which were not subjected to temperature cycling. Test specimens always exhibit a reduction in compressive strength and the reductions in strength at all temperature levels except 400°C are greater than the corresponding reductions which occurred for specimens tested either whilst hot, or after cooling. Furthermore, the reductions in strength for test temperatures of 100°C, 150°C, 250°C and 400°C are all approximately of the same order, viz. between 20% and 30% for concrete test specimens, and between 20% and 40% for mortar test specimens.

It is also apparent from the abovementioned results that for test temperatures of 150°C, 250°C and 400°C the mortar test specimens usually exhibit greater percentage reduction in compressive strength than the corresponding concrete test specimens. In some instances the difference in the reductions are as large as 15%. (This was apparent, too, for test specimens which were not subjected to temperature cycling.)

The residual ratios of compressive strength for saturated test specimens which underwent temperature cycling are shown in Figure III.18, Figure III.21 and Figure III.24 for specimens tested whilst hot; Figure III.19, Figure III.22

and Figure III.25 for specimens tested after cooling, and Figure III.20, Figure III.23 and Figure III.26 for test specimens which were cooled and immersed in water for 7 days before testing. At test temperatures of both 70°C and 100°C there is no definite trend regarding the effect of the abovementioned three test conditions on the residual ratio of compressive strength. Saturated test specimens which were heated to 70°C and subjected to temperature cycling exhibit reductions in compressive strength of between 1% and 18%. The reductions in compressive strength for saturated specimens at 100°C were between 5% and 24%, the reduction in compressive strength at 100°C always being greater than the reduction in compressive strength at 70°C. These results are in most instances the same as those which were obtained for saturated specimens which were not subjected to temperature cycling. However, the minimum residual ratios of compressive strength for specimens which were subjected to temperature cycling were larger than the minimum residual ratios of saturated specimens not subjected to temperature cycling. It does appear, therefore, that temperature cycling did not cause any additional reduction in the compressive strength of saturated test specimens.

Saturated test specimens which were subjected to temperature cycling and tested either whilst hot, or after cooling exhibit up to 15% greater reduction in compressive strength than specimens which were subjected to similar test conditions but underwent drying during heating. For the test specimens which were cooled and immersed in water for 7 days before testing the residual ratios of compressive strength for specimens which remained fully saturated during heating does not differ appreciably from the residual ratio for test specimens which underwent drying during heating.

It is of particular interest that for specimens which remained fully saturated the respective mortar and concrete test specimens usually have residual ratios of compressive strength which agree closely. A similar behavioural pattern was observed for saturated test specimens which were not subjected to temperature cycling.

From the compressive strength data reported in Sections 2.1, 2.2, 2.3 and 2.4 it appears, therefore, that:

(i) At certain temperature levels the compressive strength of test specimens may be dependent upon the heating time.

(ii) Temperature cycling does not necessarily cause additional reductions in the compressive strength. In some instances the compressive strength may increase during temperature cycling.

(iii) Concrete test specimens usually have similar percentage reductions in compressive strength, or smaller percentage reductions in compressive strength, than the corresponding mortar test specimens.

(iv) Mix proportions (apart from (iii) above) may have a significant influence on the reductions of compressive strength for test specimens which are allowed to dry during heating, particularly at the higher temperature levels.

A statistical analysis is used to elucidate (i) to (iv) above. This is reported in PART IV - STATISTICAL ANALYSIS.

CHAPTER 3 : THE ULTRASONIC PULSE VELOCITY OF HEATED CONCRETE AND MORTAR TEST SPECIMENS

The ultrasonic pulse velocity was determined on test specimens;

(i) before heating, and either
(ii) after cooling from the test temperature, or
(iii) after cooling from the test temperature and 7 days in water.

The results of these tests are given in APPENDIX II, Table A.II.1 to Table A.II.42. The data obtained from pulse velocity tests before heating were discussed in CHAPTER 1 - PROPERTIES OF THE HARDENED CONCRETE AND MORTAR MIXES. The mean pulse velocity values for the various mixes are given in CHAPTER 1. These values were used in calculating the residual ratio of pulse velocity for specimens which had been heated.

3.1 The Pulse Velocity of Test Specimens After Cooling from the Various Test Temperatures

The maximum residual ratio and minimum residual ratio of pulse velocity for test specimens cooled from the various temperature levels are illustrated in Figure III.27, Figure III.29 and Figure III.31. The maximum and minimum residual ratios in Figures III.27, III.29 and III.31 refer to the tests performed on specimens which were cooled from the various temperature levels during the period when the temperature remained constant, i.e. the pulse velocity determinations on test specimens which underwent temperature cycling are not shown. Figure III.27 shows the residual ratios of pulse velocity for the concrete mix BCY and the corresponding mortar mix BMY; the test specimens having been cooled before testing. Figure III.29 and Figure III.31 illustrate the data for mixes CCX and CMX, and for mixes CCY and CMY, respectively. The results of pulse velocity tests on specimens which remained fully saturated during heating are shown on the same diagrams as the pulse velocity data for test specimens which underwent drying during heating.

From Figure III.27, Figure III.29 and Figure III.31 it is apparent that the ultrasonic pulse velocity of test specimens is always adversely affected by heating. In general, the higher the temperature level, the lower the residual ratio of pulse velocity. It is particularly apparent from the data that the pulse velocity of mortar test specimens which underwent drying during

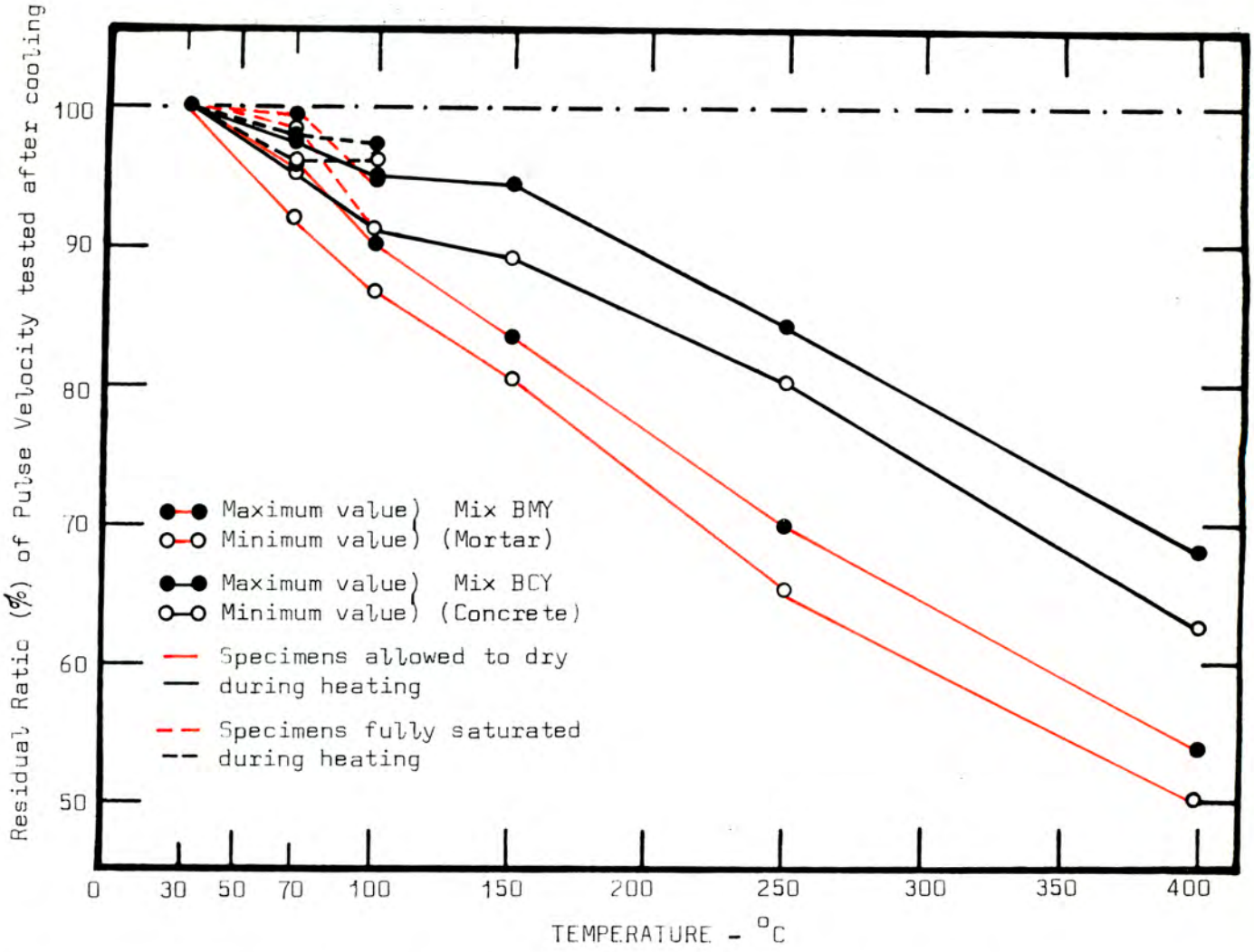


FIG.III.27: The residual ratio (%) of pulse velocity for specimens tested after cooling : Mixes BCY and BMY.

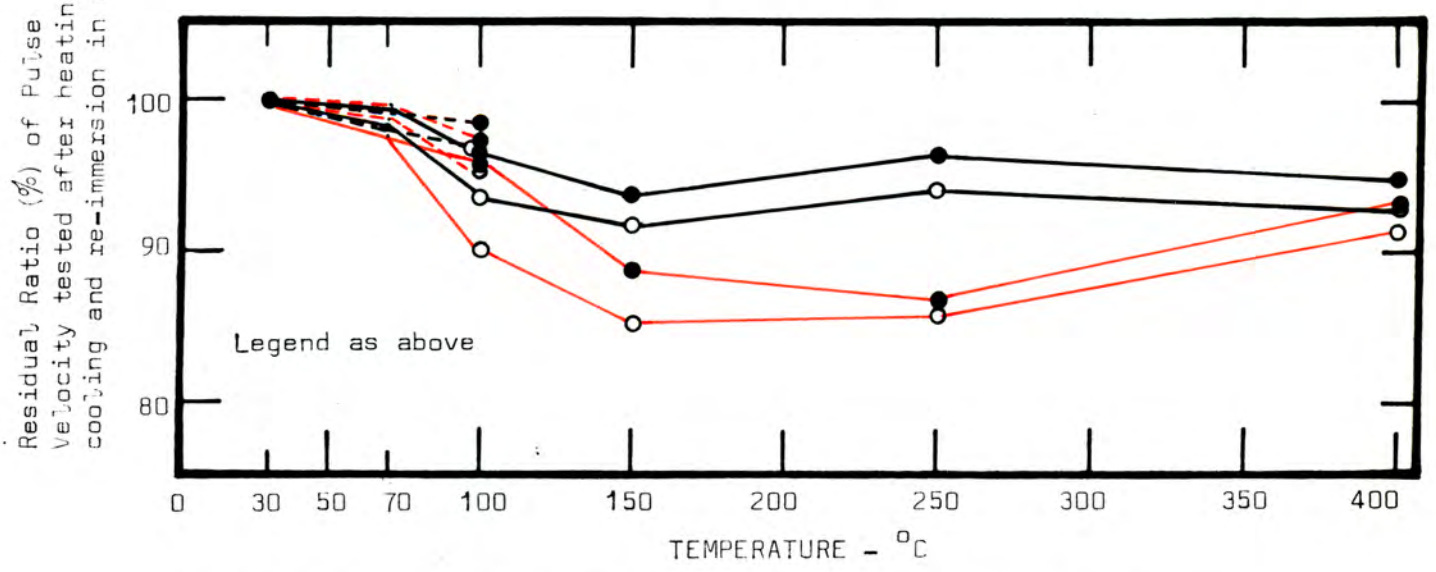


FIG.III.28: The residual ratio (%) of pulse velocity for specimens tested after re-immersion in water.

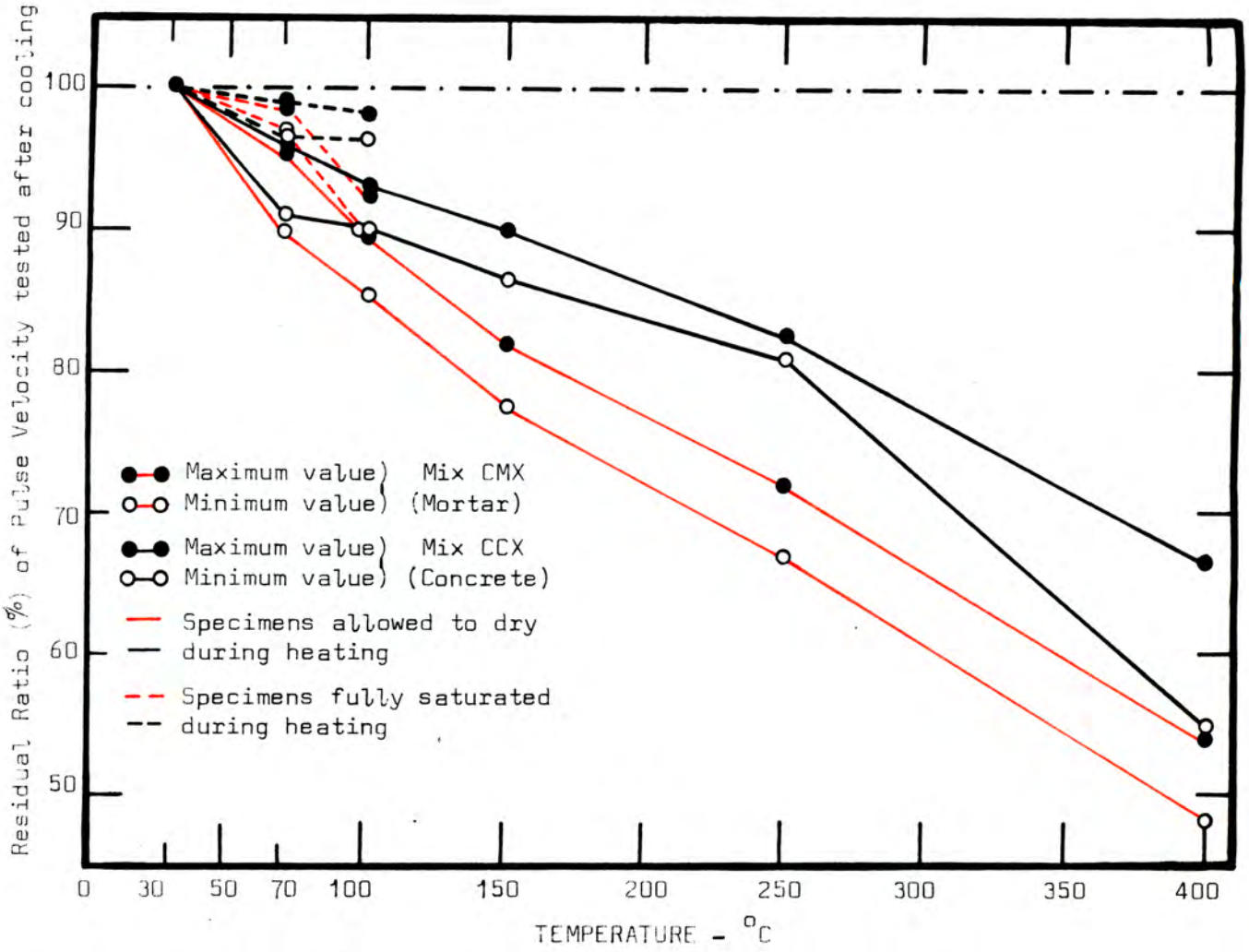


FIG.III.29: The residual ratio (%) of pulse velocity for specimens tested after cooling : Mixes CCX and CMX.

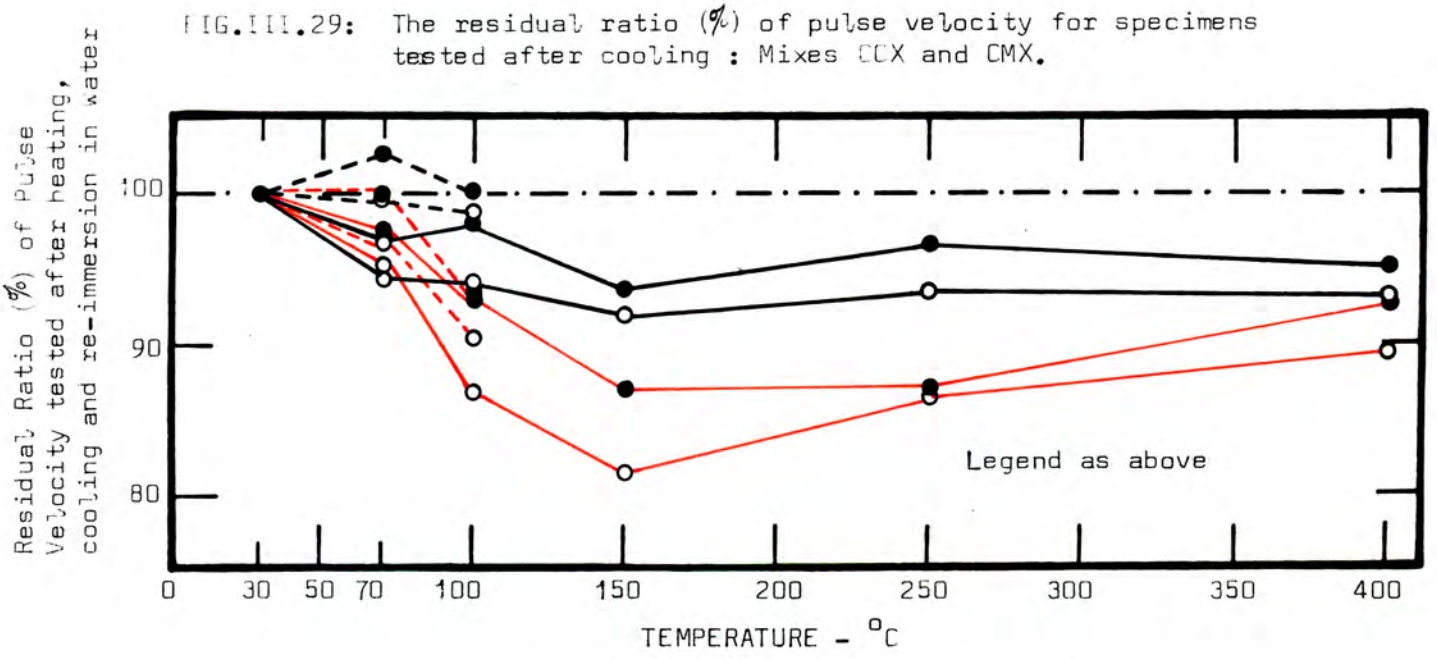


FIG.III.30: The residual ratio (%) of pulse velocity for specimens tested after re-immersion in water : Mixes CCX and CMX.

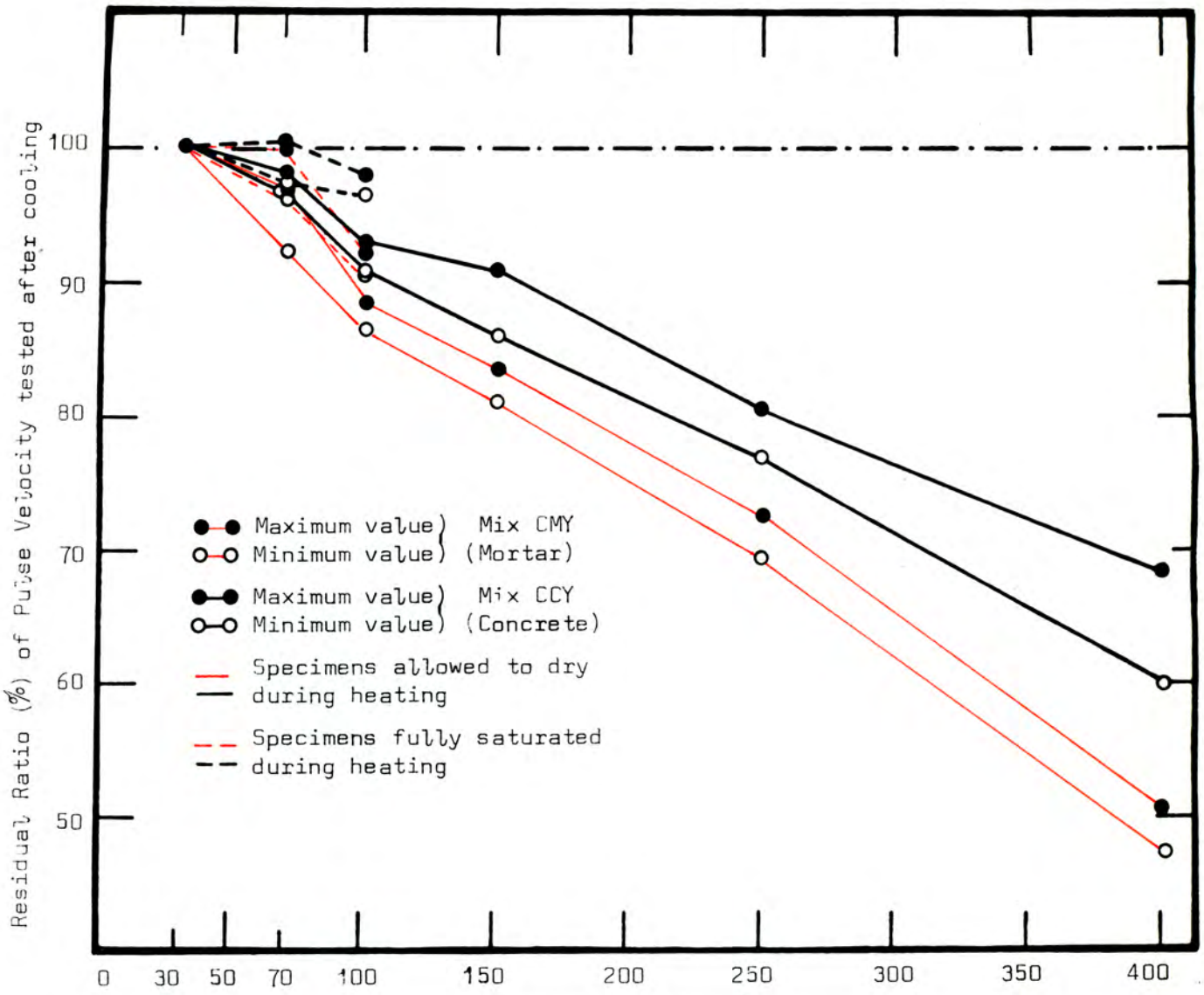


FIG.III.31: The residual ratio (%) of pulse velocity for specimens tested after cooling : Mixes CCY and CMY.

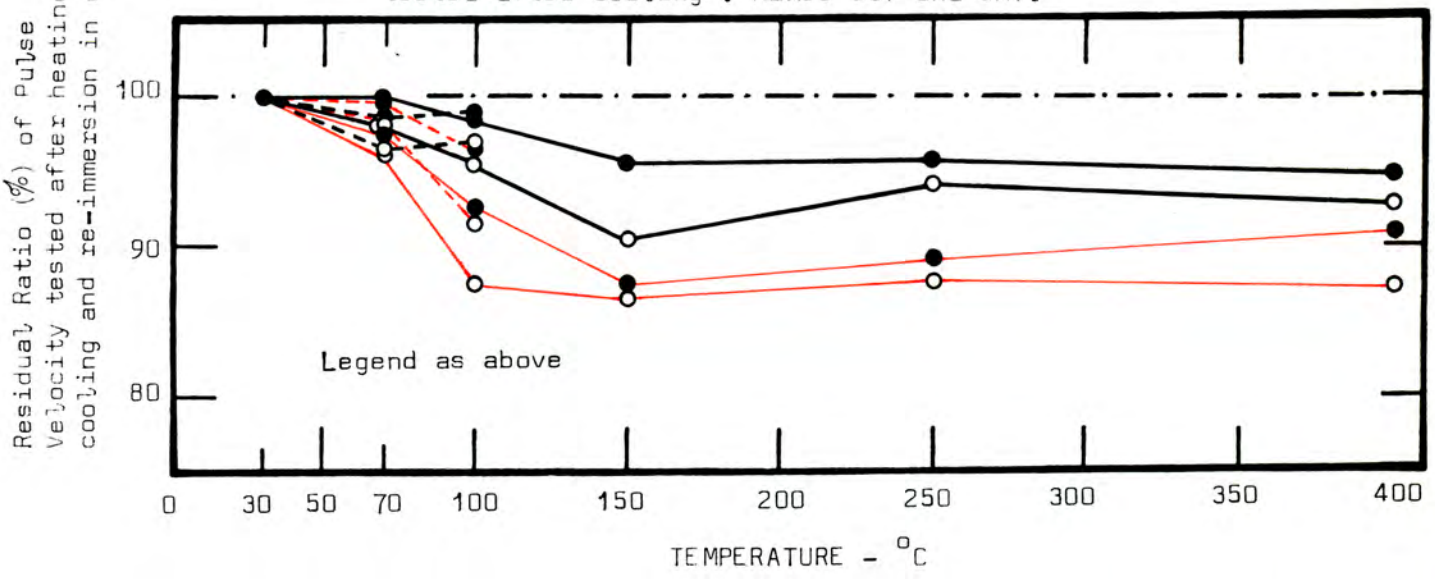


FIG.III.32: The residual ratio (%) of pulse velocity for specimens tested after re-immersion in water : Mixes CCY and CMY.

heating is always more adversely affected by heating than the pulse velocity of the corresponding concrete test specimens which underwent drying. It must be remembered, though, that the mortar test specimens had greater total water loss than the corresponding concrete test specimens. Consequently, the difference between the residual ratios of pulse velocity for mortar and concrete specimens which underwent drying is not unexpected. This is further considered in PART V : DISCUSSION AND CONCLUSIONS.

From Figure III.27, Figure III.29 and Figure II.31 it is apparent that;

(i) Test specimens which underwent drying at 70°C have residual ratios for pulse velocity which range between 91% and 98% for concrete test specimens, and between 90% and 97% for mortar test specimens. The residual ratios of pulse velocity for specimens which remained fully saturated at 70°C are approximately the same for concrete and mortar test specimens and range between 96% and 100%. For a particular mix, the residual ratios of pulse velocity for specimens which remained fully saturated during heating is usually higher than the residual ratios of pulse velocity for test specimens which underwent drying during heating.

(ii) The residual ratios of pulse velocity for specimens which underwent drying at 100°C, and for specimens that remained fully saturated at 100°C, are always lower than the corresponding residual ratios of pulse velocity for test specimens at 70°C. For specimens that were allowed to dry at 100°C the residual ratios range between 90% and 95% for concrete test specimens and from 85% to 90% for mortar specimens. The residual ratios of pulse velocity for specimens which remained fully saturated at 100°C range between 96% and 98% for concrete test specimens and from 90% to 95% for mortar test specimens. For test specimens which underwent drying during heating, as well as test specimens which remained fully saturated during heating, the residual ratio of pulse velocity for mortar test specimens is lower than the residual ratio of pulse velocity for concrete specimens; the maximum difference for specimens which remained fully saturated is 7%.

(iii) The residual ratio of pulse velocity at 150°C is always smaller than the residual ratio of pulse velocity at 100°C. Values range from 86% to 94% for concrete test specimens and from 77% to 84% for mortar test specimens.

(iv) Test specimens which were heated to 250°C have residual ratios of pulse velocity which range from 77% to 84% for concrete specimens and from 65% to 73% for mortar test specimens.

(v) The lowest residual ratios of pulse velocity occur for test specimens heated to 400°C. Residual ratios for the concrete specimens are between 55% and 70%, and range from 48% to 54% for the mortar test specimens.

3.2 The Ultrasonic Pulse Velocity of Test Specimens which were Cooled and Immersed in Water for 7 days before Testing

The maximum residual ratios and minimum residual ratios of pulse velocity are shown in Figure III.28 for the concrete mix BCY and the corresponding mortar mix BMY, in Figure III.30 for the mixes CCX and CMX, and in Figure III.32 for the mixes CCY and CMY. The residual ratios of pulse velocity for test specimens which were subjected to temperature cycling are not included in these graphs, i.e. Figure III.28, Figure III.30 and Figure III.32 show the maximum and minimum residual ratios of test specimens which were removed from the furnace (waterbath) at various times during the period when the test temperature remained constant.

From Figure III.28, Figure III.30 and Figure III.32 it is apparent that:

(i) The residual ratios of pulse velocity for test specimens which underwent drying at either 70°C, 100°C, 150°C, 250°C or 400°C, and were cooled and immersed in water for 7 days before testing, are always higher than the residual ratios of pulse velocity for specimens which were tested immediately after cooling from these temperature levels. The percentage difference between the respective residual ratios ranges between 5% for specimens cooled from 70°C to 40% for test specimens cooled from 400°C. Test specimens which remained fully saturated at either 70°C or 100°C have residual ratios of pulse velocity which do not differ appreciably for the abovementioned two test cases.

(ii) The residual ratios of pulse velocity for test specimens which underwent drying at either 70°C, 100°C, 150°C, 250°C or 400°C and were cooled and immersed in water for 7 days are always lower for mortar test specimens than for the corresponding concrete test specimens. This is of particular interest since these results apply to test specimens which were re-saturated, i.e. the pulse velocity results are not affected by the difference in water loss between the concrete and mortar test specimens, as was the case in 3.1 above.

(iii) Test specimens which underwent drying at 70°C and were cooled and immersed in water for 7 days before testing have residual ratios which range between 95% and 100% for concrete specimens and from 95% to 98% for mortar specimens. Concrete test specimens which remained fully saturated at 70°C have residual ratios of pulse velocity which agree closely with those for mortar test specimens that remained fully saturated at 70°C; these values range between 97% and 100%.

(iv) Test specimens which were allowed to dry at 100°C as well as specimens which remained fully saturated at 100°C, have lower residual ratios of pulse velocity than the corresponding specimens at 70°C. The residual ratios of pulse velocity for specimens that underwent drying at 100°C range from 93% to 98% for concrete specimens and between 87% and 96% for mortar specimens. In general, the residual ratios of pulse velocity for specimens which remained fully saturated at 100°C are larger than the residual ratios for specimens which underwent drying. The residual ratios of concrete specimens which remained fully saturated at 100°C range from 97% to 100%, and for mortar specimens from 90% to 97%.

(v) The residual ratios of pulse velocity for concrete and mortar specimens cooled from 150°C and immersed in water for 7 days before testing are lower than the corresponding residual ratios for specimens at either 70°C or 100°C. The values range from 90% to 96% for concrete test specimens and from 81% to 89% for mortar test specimens.

(vi) Test specimens which were cooled from either 250°C or 400°C and immersed in water for 7 days before testing, have residual ratios of pulse velocity which are usually <u>greater</u> than the residual ratios of pulse velocity for the corresponding specimens at 150°C. At these

temperature levels the concrete and mortar specimens have residual ratios which are approximately the same as those for the corresponding concrete and mortar test specimens at 100°C. The residual ratios of pulse velocity for concrete specimens heated to 250°C range between 93% and 97%, and between 85% and 89% for mortar test specimens heated to 250°C. For specimens heated to 400°C the residual ratios range from 92% to 95% for concrete test specimens and from 87% to 93% for mortar test specimens. It is particularly apparent that the differences between the respective residual ratios of concrete and mortar specimens heated to 400°C are not as large as those at either 150°C or 250°C.

3.3 The Ultrasonic Pulse Velocity of Test Specimens Subjected to Temperature Cycling

The results of pulse velocity determinations on test specimens which were subjected to temperature cycling are shown in Figure III.27(a) to Figure III.32(a). Figure III.27(a), Figure III.29(a) and Figure III.31(a) illustrate the maximum and minimum residual ratios for mixes BCY and BMY, mixes CCX and CMX, and mixes CCY and CMY, respectively, the pulse velocity having been measured immediately after test specimens had cooled from the various temperature levels. In Figure III.28(a), Figure III.30(a) and Figure III.32(a) the residual ratios of pulse velocity for specimens which were cooled from the respective test temperatures and immersed in water for 7 days before testing, are illustrated. Figure III.28(a) shows the data for mixes BCY and BMY, Figure III.30(a) the data for mixes CCX and CMX, and Figure III.32(a) the data for mixes CCY and CMY. It is apparent that the behavioural pattern exhibited by these results is exactly similar to that shown by the data for test specimens which were not subjected to temperature cycling. In most instances the residual ratios of pulse velocity for specimens subjected to temperature cycling are very similar to the residual ratios for specimens not subjected to temperature cycling. The exception to this occurred for test specimens which underwent drying during heating and were tested immediately after cooling; in this case the residual ratios of pulse velocity for specimens which underwent temperature cycling are usually lower than the residual ratios for specimens not subjected to temperature cycling. The difference between the respective residual ratios range between 1% and 5%.

It is particularly noticeable in the abovementioned pulse velocity results (both for specimens which underwent temperature cycling and specimens which were not subjected to temperature cycling) that the maximum and minimum residual ratio for a particular concrete or mortar mix at a particular

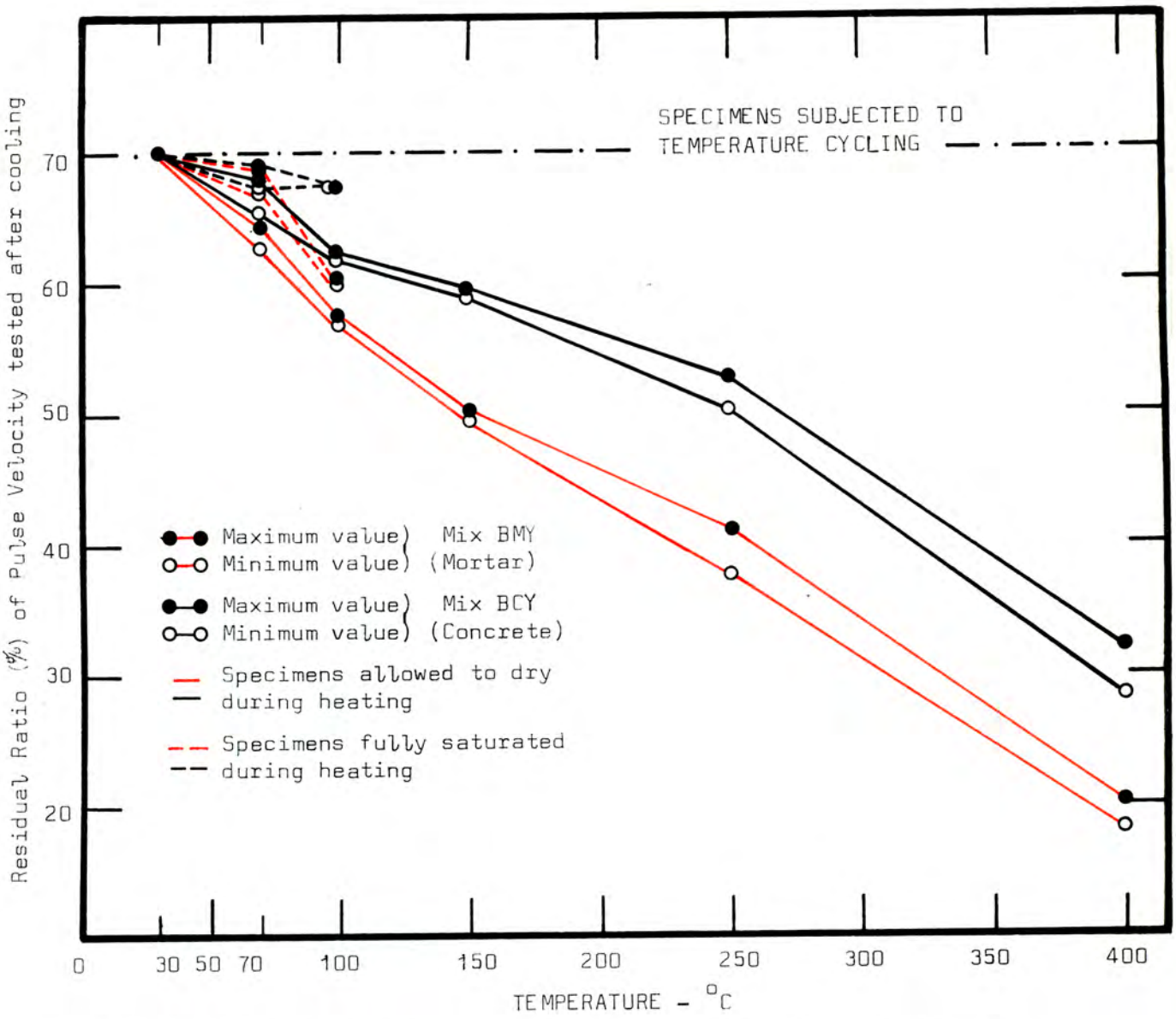


FIG.III.27(a): The residual ratio (%) of pulse velocity for specimens tested after cooling : Mixes BCY and BMY.

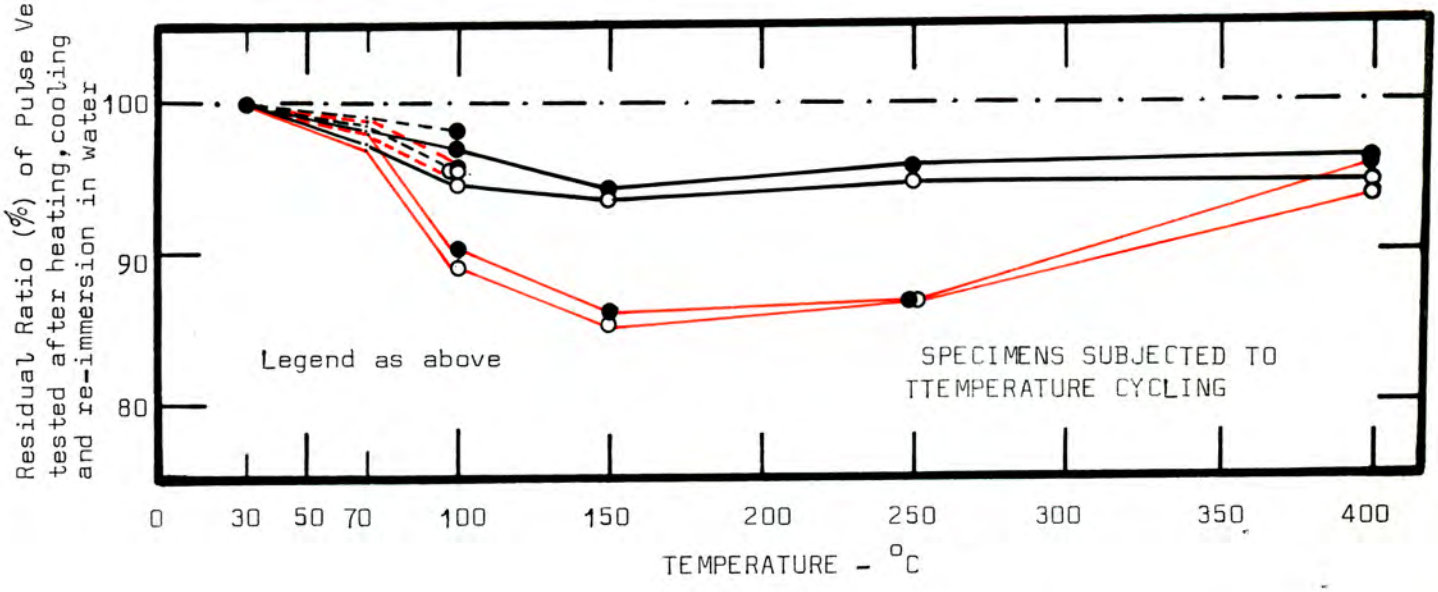


FIG.III.28(a): The residual ratio (%) of pulse velocity for specimens tested after re-immersion in water : Mixes BCY and BMY.

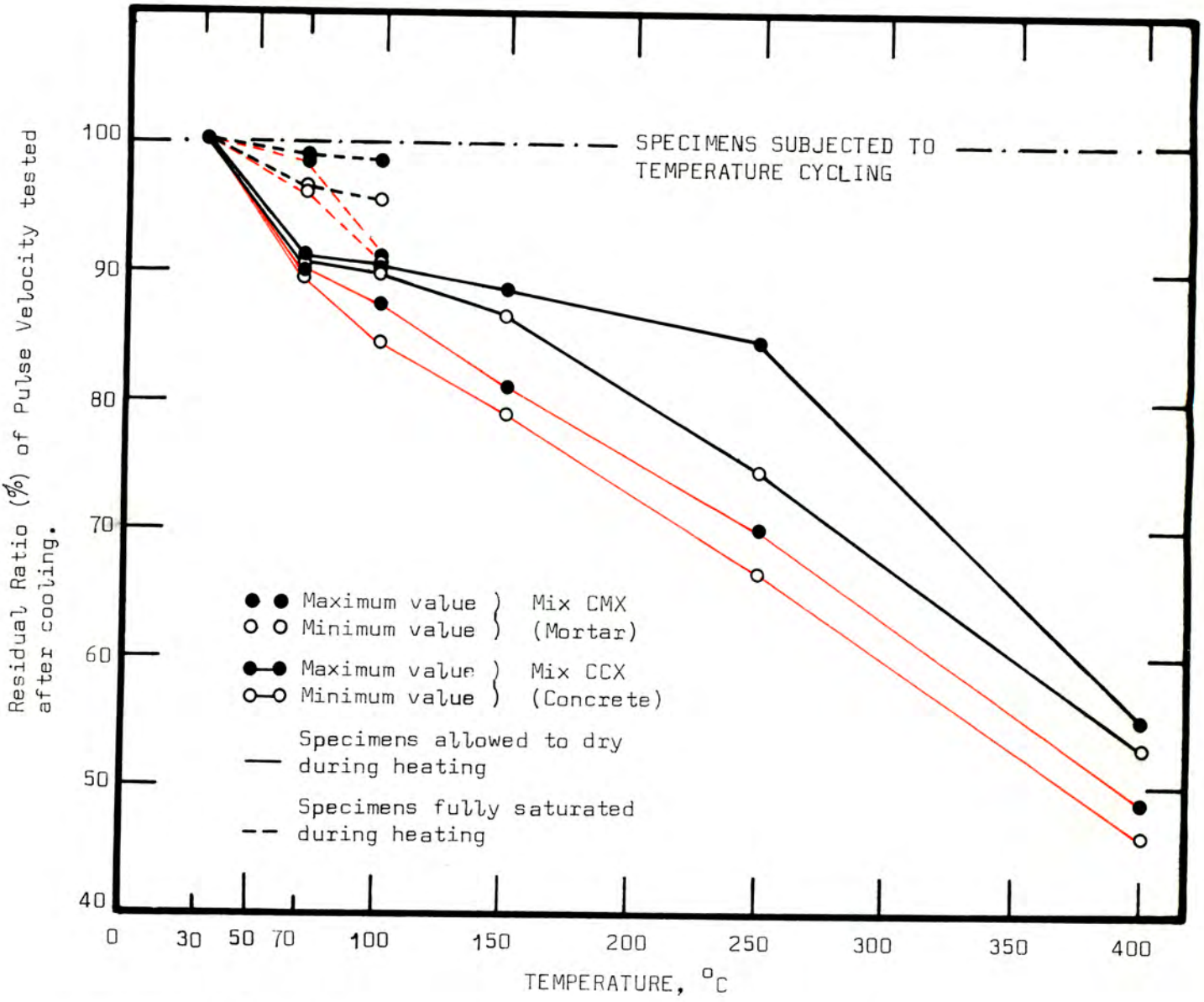


FIG.III.29(a): The residual ratio (%) of pulse velocity for specimens tested after cooling : Mixes CCX and CMX.

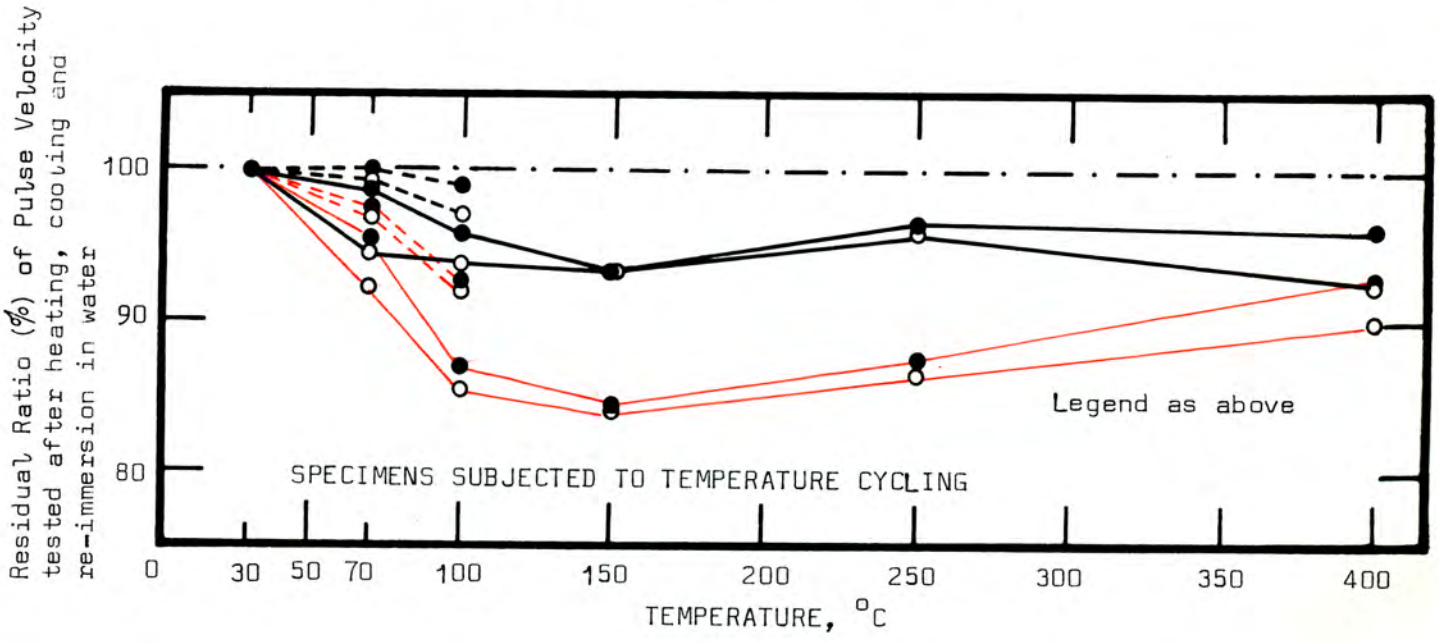


FIG.III.30(a): The residual ratio (%) of pulse velocity for specimens tested after re-immersion in water : Mixes CCX and CMX.

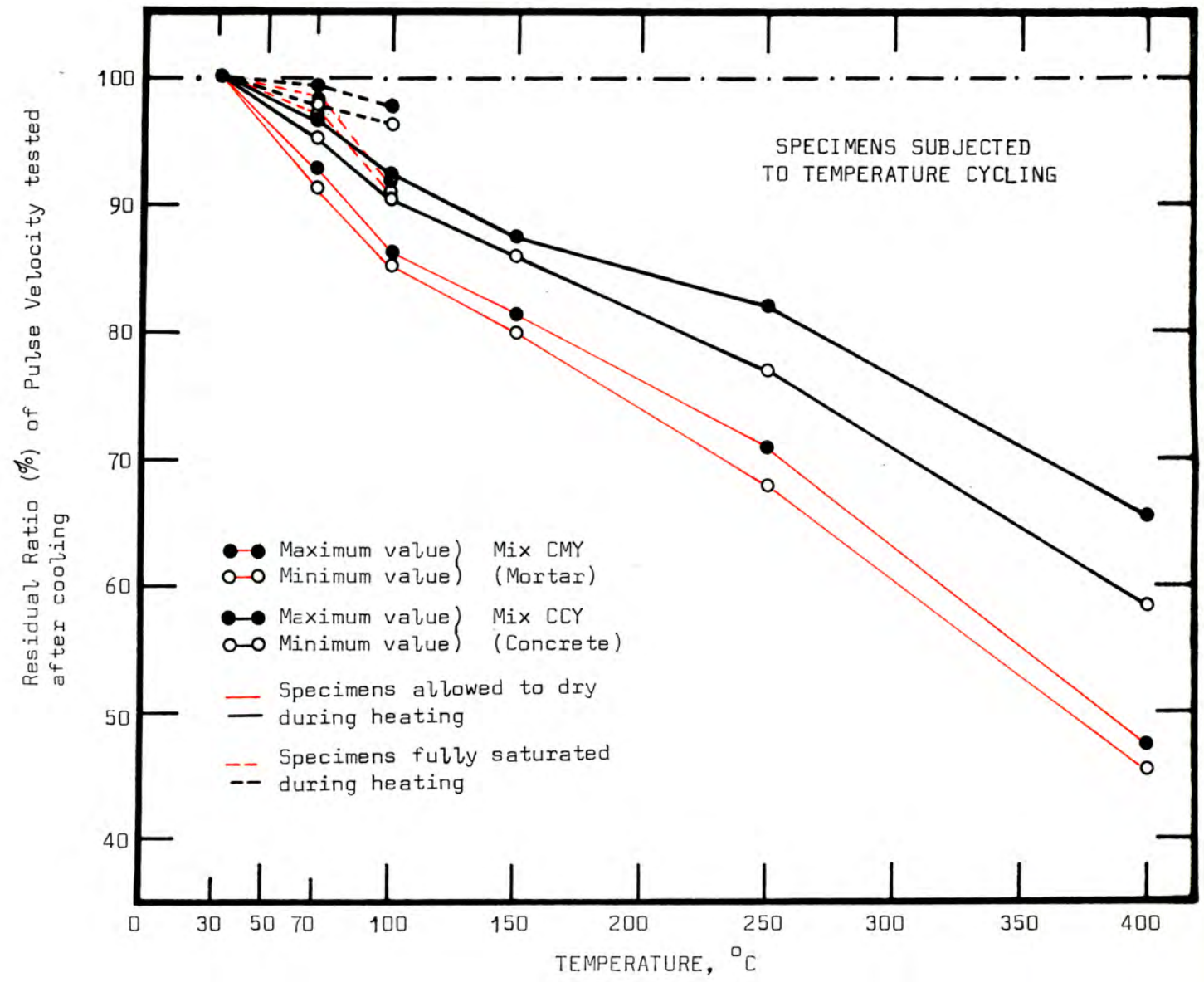


FIG.III.31(a): The residual ratio (%) of pulse velocity for specimens tested after cooling : Mixes CCY and CMY.

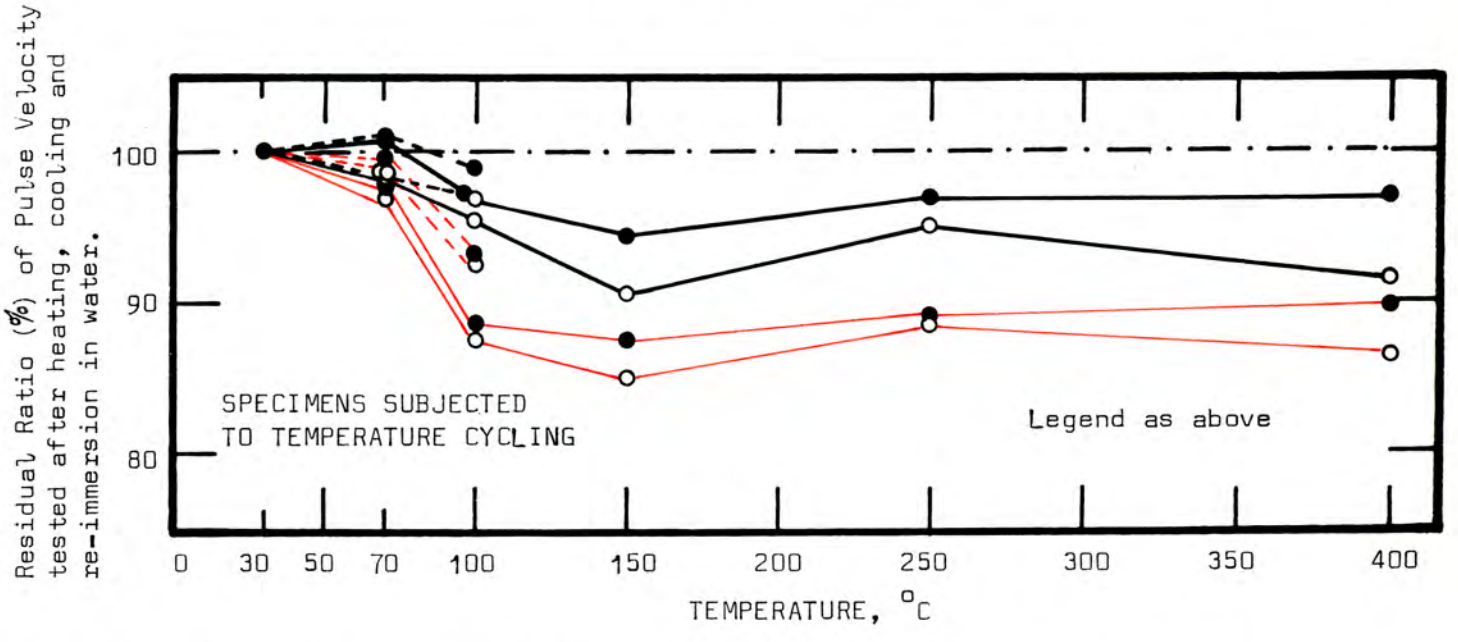


FIG.III.32(a): The residual ratio (%) of pulse velocity for specimens tested after re-immersion in water : Mixes CCY and CMY.

temperature level usually differ by less than 5%. The exception to this occurred for concrete test specimens which were cooled from 400°C. Furthermore, the respective maximum residual ratios of pulse velocity for the various concrete mixes (as well as the minimum residual ratios) tested at a particular temperature usually differ by less than 5%). This is apparent, too, for the various mortar mixes. It appears therefore, that:

(i) the pulse velocity values determined on test specimens which were removed from the furnace (waterbath) at various times during the period when the test temperature remained constant are not significantly affected by the heating time.

(ii) At a particular temperature level the residual ratios of pulse velocity for the various concrete mixes do not differ significantly.

(iii) At a particular temperature level the residual ratios of pulse velocity for the various mortar mixes do not differ significantly.

However, it should be remembered that for a particular mix, the coefficient of variation for the pulse velocity control tests was always less than 2.5%. Consequently, a statistical analysis has to be carried out to determine whether the assumptions (i) to (iii) above are correct. The statistical analysis will also elucidate the effect of temperature cycling on the pulse velocity. This analysis is given in PART IV : STATISTICAL ANALYSIS.

CHAPTER 4 : THE DYNAMIC YOUNG'S MODULUS OF CONCRETE AND MORTAR TEST SPECIMENS SUBJECTED TO HEATING

The dynamic Young's modulus was determined on test specimens:

(i) before heating, and either

(ii) after cooling from the test temperature, or

(iii) after cooling from the test temperature and 7 days in water.

The results of these tests are tabulated in APPENDIX II, Table A.II.1 to Table A.II.42. The values of dynamic Young's modulus obtained from the control tests were discussed in CHAPTER 1 : PROPERTIES OF THE HARDENED CONCRETE AND MORTAR MIXES. For each mix a best estimate for the mean value of the dynamic Young's modulus of unheated specimens was determined. These values were used in calculating the residual ratio of dynamic Young's modulus for specimens which were subjected to heating.

4.1 The Dynamic Young's Modulus of Specimens Tested Immediately after Cooling from the Various Test Temperatures

The maximum residual ratio and minimum residual ratio of the dynamic Young's modulus for test specimens which were cooled from the various test temperatures are shown in Figure III.33 for the concrete mix BCY and the mortar mix BMY, Figure III.35 for the concrete mix CCX and the mortar mix CMX, and Figure III.37 for the mixes CCY and CMY. Each figure shows the data for the test specimens which underwent drying during heating as well as the data for test specimens which remained fully saturated during heating. These data do not include values of the residual ratio obtained from tests on specimens which were subjected to temperature cycling.

The results shown in Figure III.33, Figure III.35 and Figure III.37 for specimens that underwent drying during heating indicate that:

(i) The dynamic Young's modulus is always reduced when concrete or mortar test specimens are heated. In general, the higher the temperature, the greater the reduction in dynamic Young's modulus.

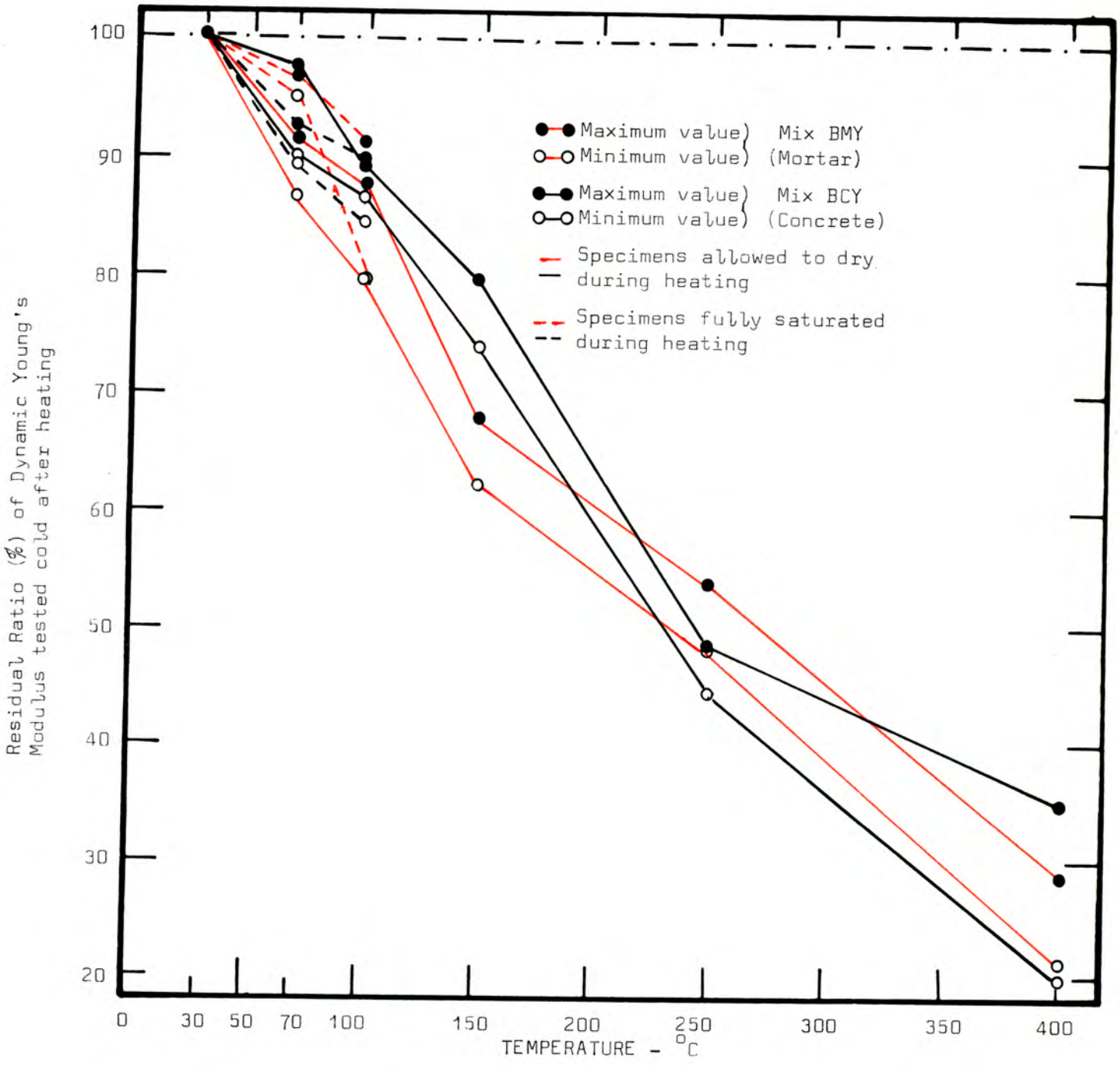


FIG.III.33: The residual ratio (%) of dynamic Young's Modulus for specimens tested after cooling : Mixes BCY and BMY.

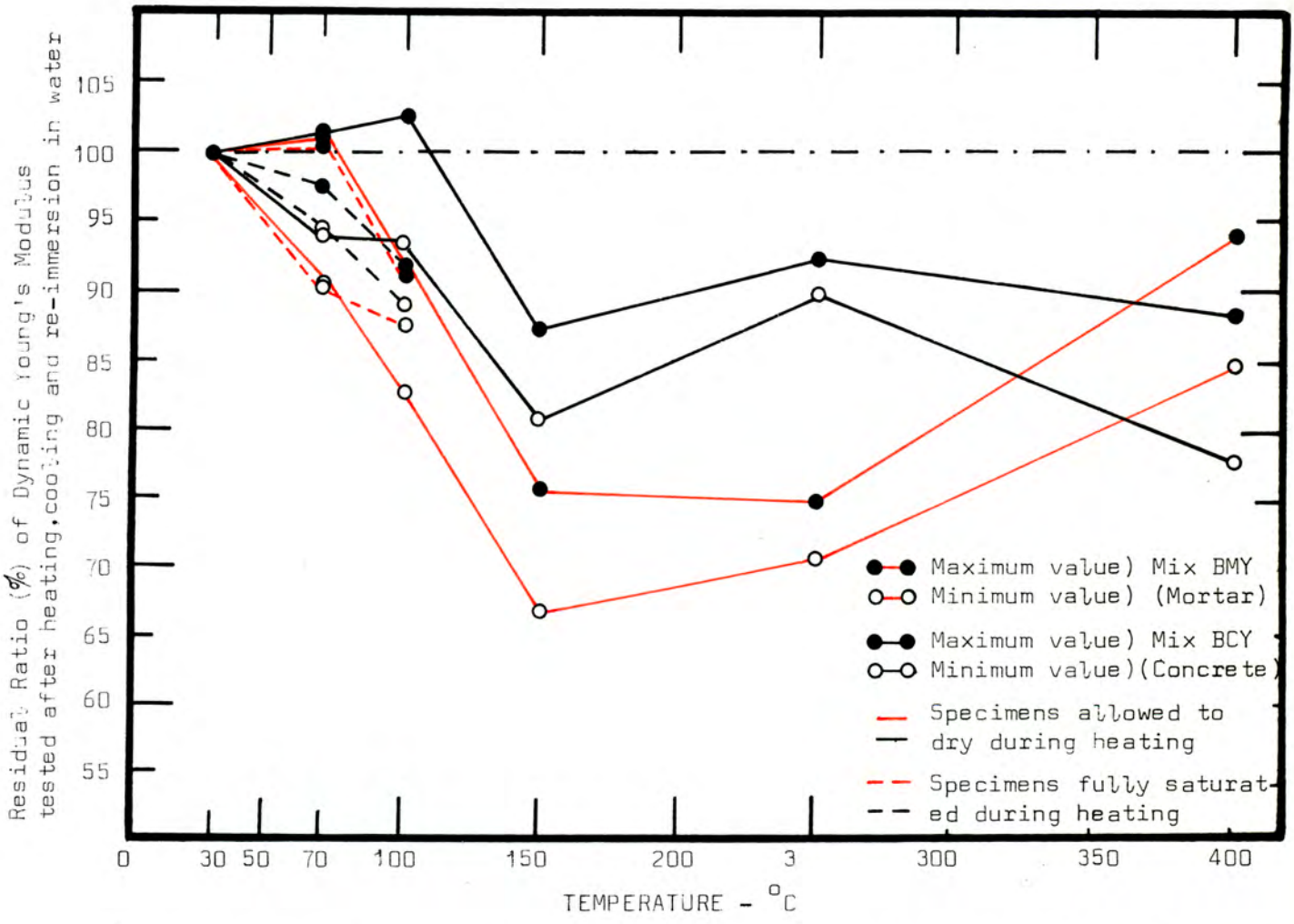


FIG.III.34: The residual ratio (%) of dynamic Young's Modulus for specimens tested after re-immersion in water : Mixes BCY and BMY.

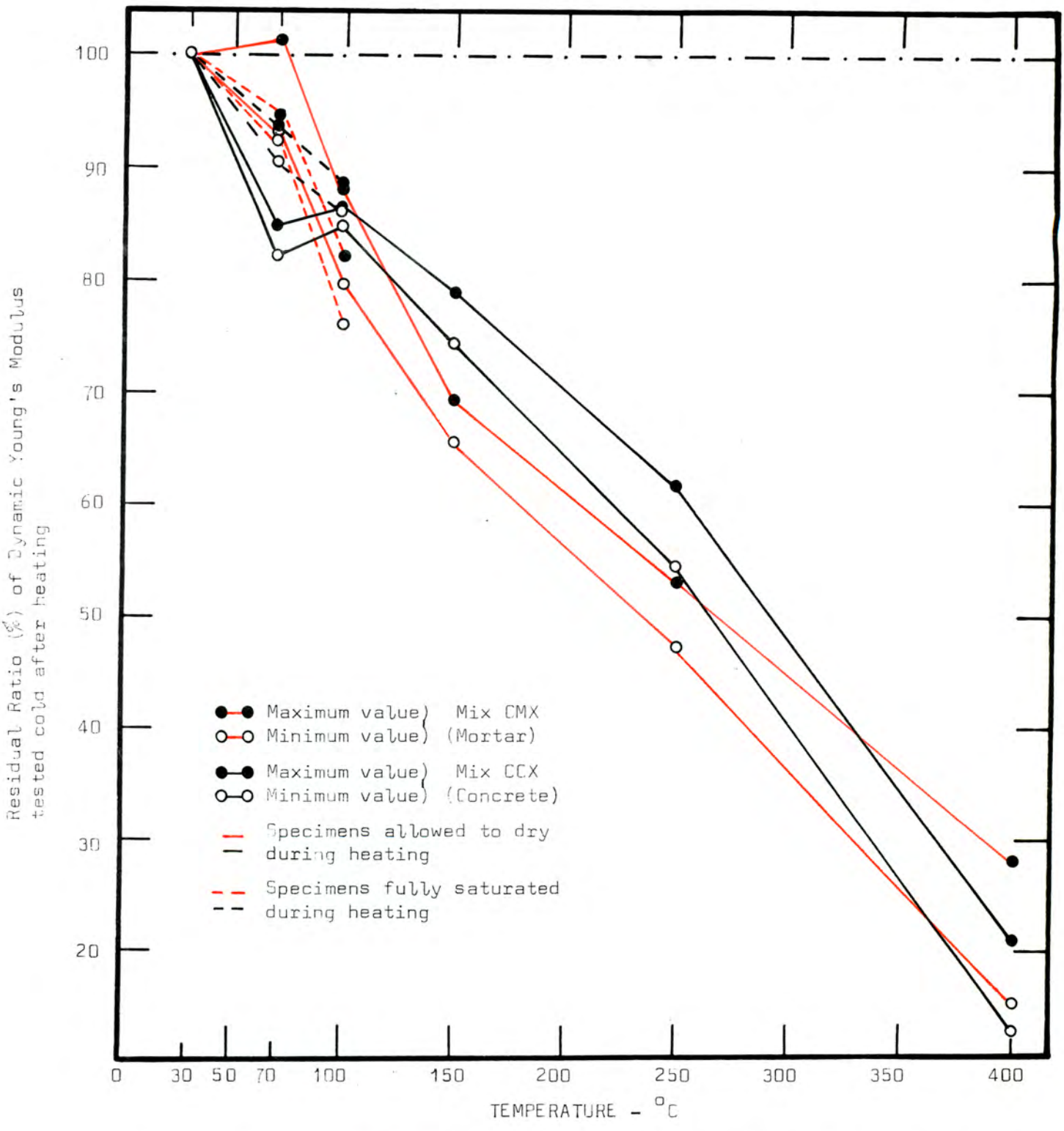


FIG.III.35: The residual ratio (%) of dynamic Young's Modulus for specimens tested after cooling : Mixes CCX and CMX.

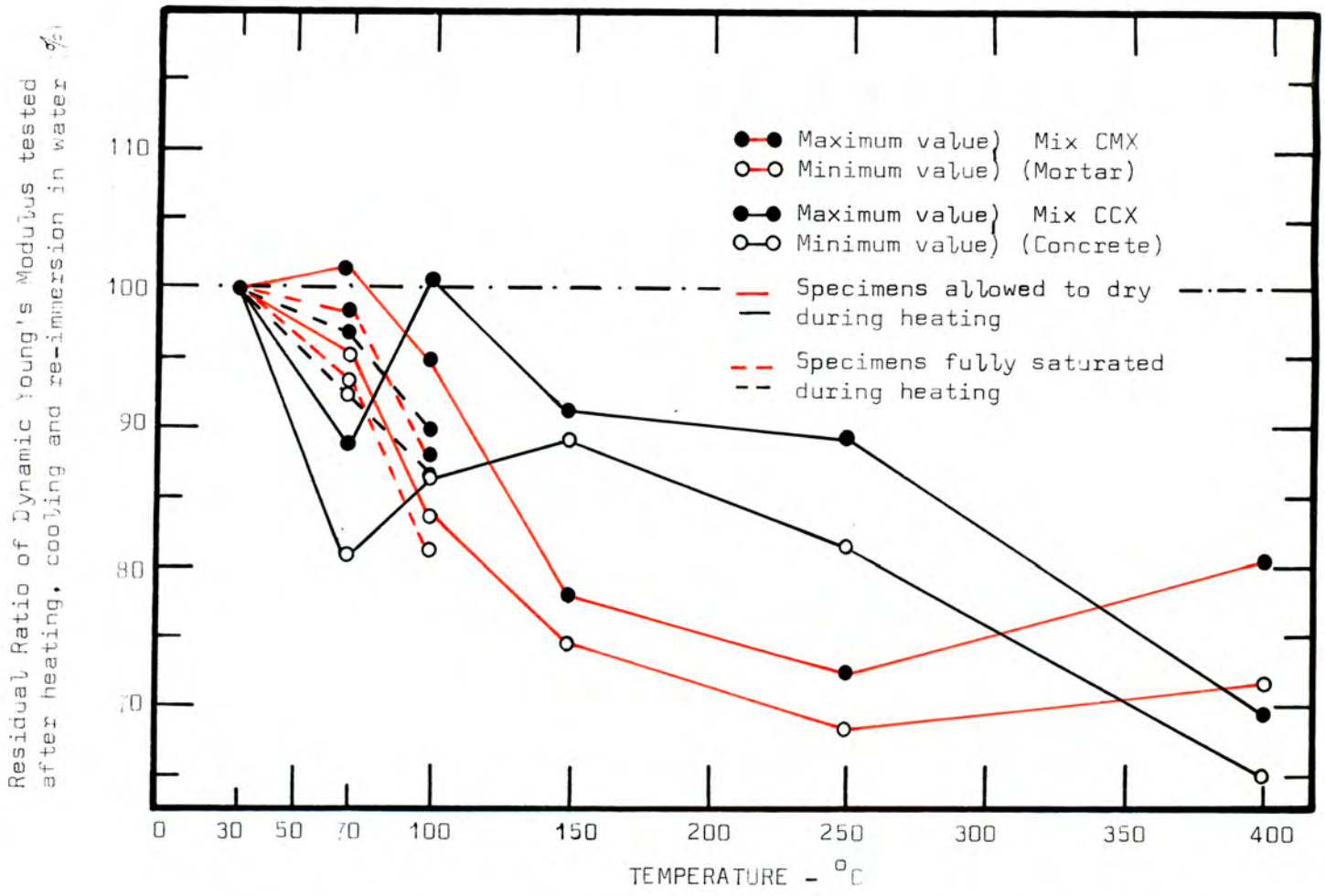


FIG.III.36: The residual ratio (%) of dynamic Young's Modulus for specimens tested after re-immersion in water : Mixes CCX and CMX.

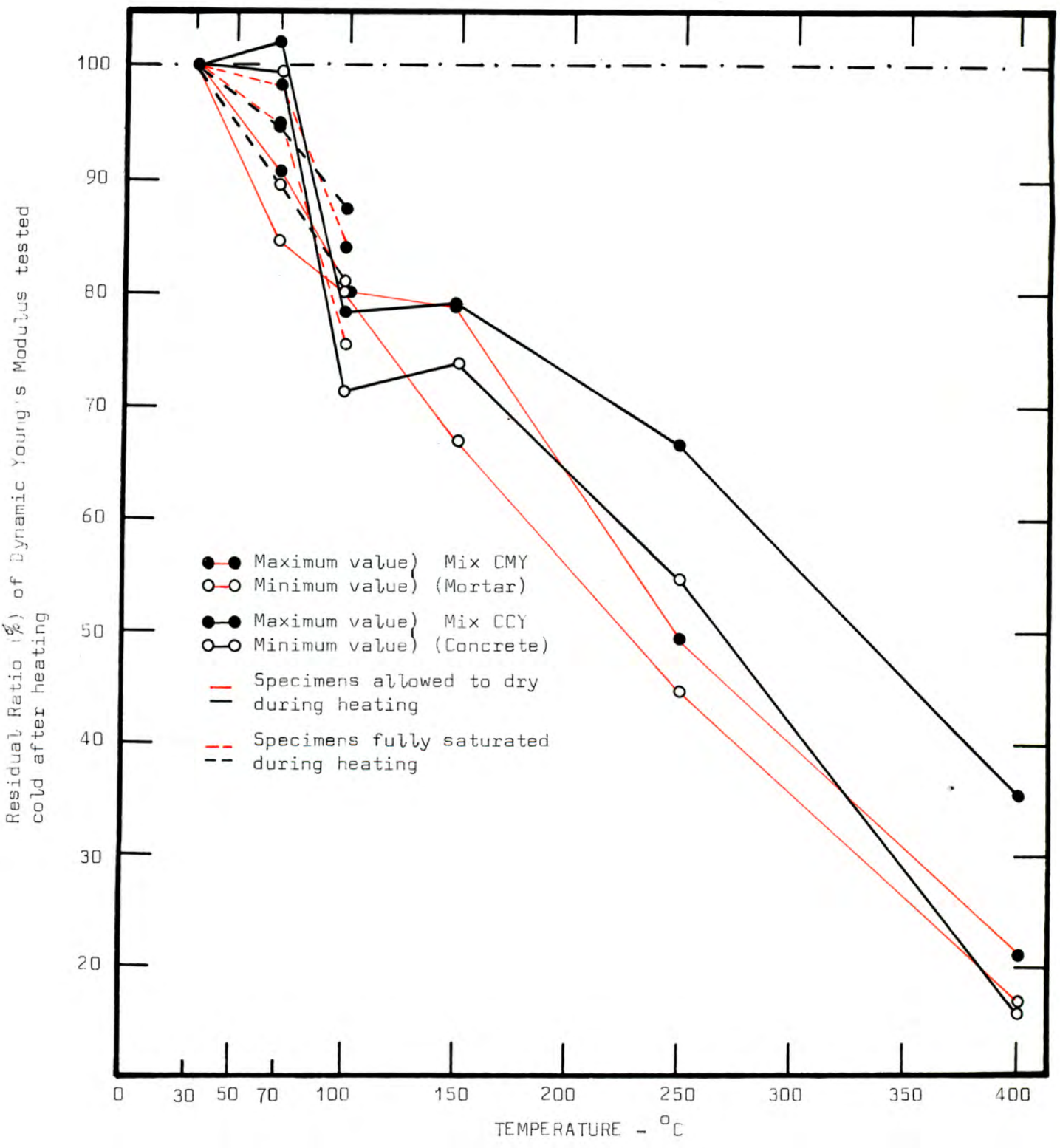


FIG.III.37: The residual ratio (%) of dynamic Young's Modulus for specimens tested after cooling : Mixes CCY and CMY.

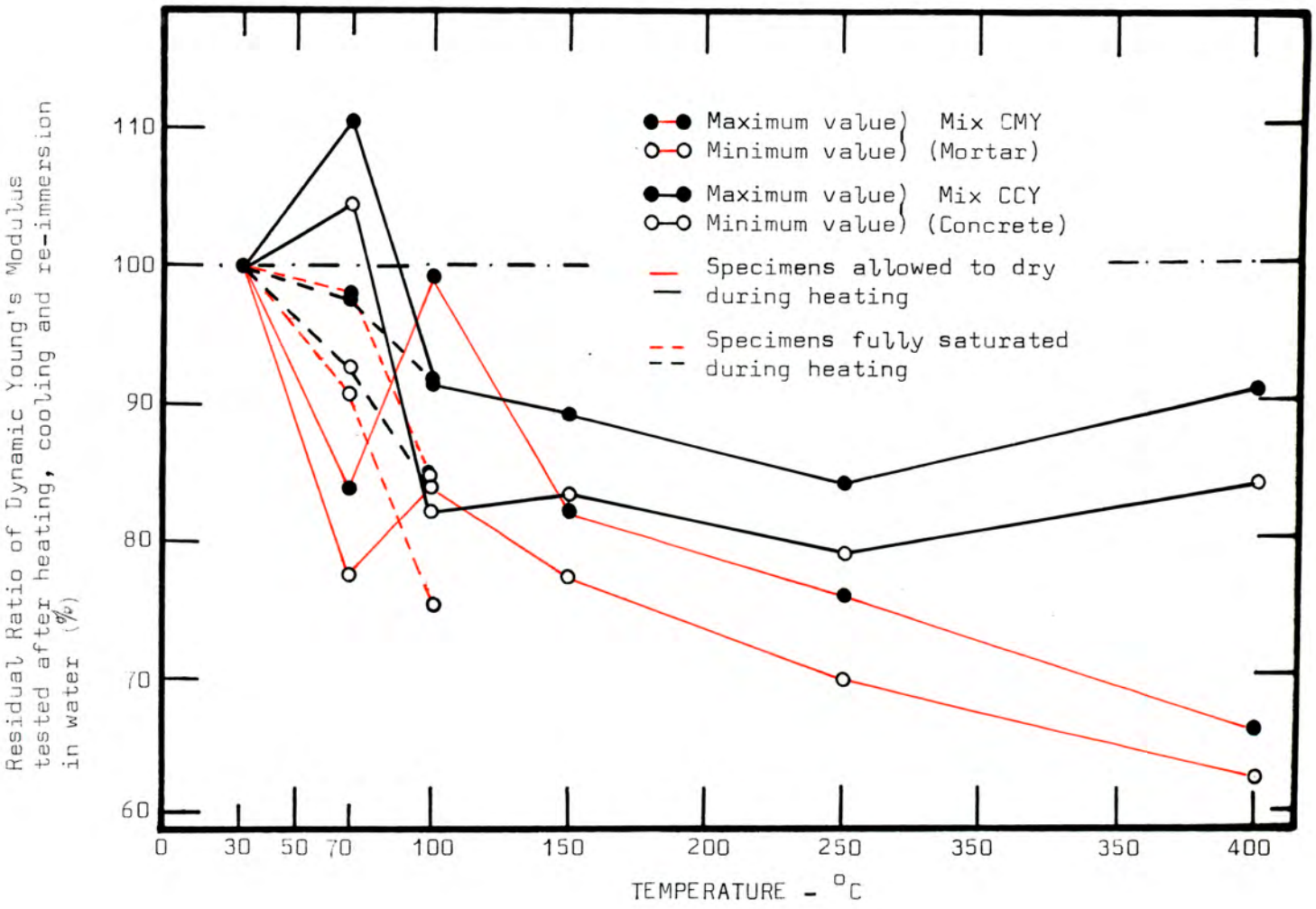


FIG.III.38: The residual ratio (%) of dynamic Young's Modulus for specimens tested after re-immersion in water : Mixes CCY and CMY.

(ii) The residual ratios of dynamic Young's modulus for concrete test specimens that were cooled from 70°C before testing are markedly different for the three concrete mixes, viz. the maximum and minimum residual ratios of dynamic Young's modulus for mix BCY are 98% and 90% respectively, whereas the maximum and minimum residual ratios for mix CCX are 85% and 82% respectively, and those for mix CCY are 102% and 99%. Similar behaviour occurred for the mortar test specimens cooled from 70°C before testing; the maximum and minimum residual ratios of dynamic Young's modulus for mix BMY are 94% and 87% respectively, those for mix CMX are 101% and 93%, and for mix CMY the maximum and minimum residual ratios are 91% and 84% respectively.

(iii) The residual ratio of dynamic Young's modulus for specimens cooled from 100°C before testing range between 72% and 90% for concrete test specimens, and from 80% to 90% for specimens made from the various mortar mixes. It is again apparent that the residual ratios of the three concrete mixes, as well as those of the three mortar mixes, differ widely.

(iv) Test specimens cooled from 150°C before testing have residual ratios of dynamic Young's modulus which range between 74% and 80% for concrete specimens, and from 62% to 79% for mortar specimens. It appears that at this temperature level the residual ratios of dynamic Young's modulus for concrete test specimens are always higher than the residual ratios of dynamic Young's modulus for mortar test specimens.

(v) The residual ratios of dynamic Young's modulus for specimens cooled from 250°C range between 44% and 66% for concrete test specimens, the residual ratios for the concrete mix BCY being approximately 10% lower than the residual ratios of the concrete mixes CCX and CCY. The mortar test specimens cooled from 250°C have residual ratios of dynamic Young's modulus which range from 45% to 54%.

(vi) Test specimens cooled from 400°C exhibit the greatest reduction in dynamic Young's modulus. Concrete test specimens exhibit reductions of between 65% and 90%, and the reductions in dynamic Young's modulus for mortar specimens are between 70% and 85%.

Test specimens which remained fully saturated at temperatures of either 70°C or 100°C and were tested after cooling from these temperatures, always exhibit a reduction in dynamic Young's modulus. The residual ratios of saturated concrete specimens cooled from 70°C range from 90% to 95%, and from 90% to 98% for saturated mortar specimens cooled from 70°C. In general, the residual ratios of the mortar test specimens appear to be greater than the residual ratios of the corresponding concrete test specimens. Specimens which remained fully saturated at 100°C always have lower residual ratios of dynamic Young's modulus than specimens which remained saturated at 70°C. Concrete specimens cooled from 100°C have residual ratios which range between 80% and 90%. The mortar test specimens have residual ratios which range between 76% and 90%, i.e. the mortar test specimens exhibit reductions in dynamic Young's modulus which are either similar to or greater than the reductions which occurred for the concrete specimens.

4.2 The Dynamic Young's Modulus of Specimens which were Cooled and Immersed in Water for 7 Days before Testing

The maximum and minimum residual ratios of dynamic Young's modulus for specimens which were cooled and immersed in water for 7 days before testing are shown in Figure III.34, Figure III.36 and Figure III.38. Figure III.34 illustrates the maximum and minimum residual ratios for the concrete mix BCY and the corresponding mortar mix BMY, Figure III.36 the residual ratios for mixes CCX and CMX, and Figure III.38 the residual ratios for mixes CCY and CMY. These data do not include the residual ratios of specimens which were subjected to temperature cycling.

The results for test specimens which underwent drying during the heating period indicate that:

(i) The residual ratios of dynamic Young's modulus for concrete specimens cooled from 70°C and immersed in water for 7 days before testing usually range between 81% and 110%. The three respective concrete mixes have widely different residual ratios, e.g. the residual ratios of mix BCY range from 81% to 89%, whereas the residual ratios of mix CCY range between 105% and 110%. The mortar mixes which were cooled from 70°C and immersed in water for 7 days before testing also exhibit wide variations between the residual ratios for the respective mixes. The residual ratios of dynamic Young's modulus for the mortar mix CMY are between 78% and 84% whereas the residual ratios of the mortar mixes BMY and CMX range from 91% to 101%. The

residual ratios of both concrete and mortar specimens are usually the same as, or up to 10% higher than, the residual ratios for specimens which were tested immediately after cooling from 70°C.

(ii) Concrete test specimens cooled from 100°C and immersed in water for 7 days before testing have residual ratios which range between 81% and 103%. As with specimens which were cooled from 70°C and immersed in water before testing, the residual ratios of the various concrete mixes are widely different. The concrete mix BCY exhibits residual ratios between 93% and 103%, mix CCX has residual ratios ranging from 86% to 100% and the residual ratios for mix CCY range between 82% and 91%. The residual ratios of dynamic Young's modulus for test specimens made from the various mortar mixes range between 83% and 99%. It appears that the reduction in dynamic Young's modulus for the mortar test specimens is either the same as, or greater than, the reduction incurred by the corresponding concrete test specimens. Furthermore, it appears that for both concrete and mortar specimens the reduction in dynamic Young's modulus of specimens cooled and re-immersed in water is between 5% and 10% less than the reduction exhibited by the corresponding test specimens which were tested immediately after cooling.

(iii) The residual ratios of dynamic Young's modulus for concrete test specimens cooled from 150°C and immersed in water for 7 days before testing, range from 80% to 91%, and those for mortar specimens from 67% to 82%, i.e. the mortar test specimens always have between 10% and 15% greater reduction in dynamic Young's modulus than concrete test specimens. The residual ratios are between 5% and 10% higher than the residual ratios for concrete and mortar test specimens which were tested immediately after cooling from 150°C.

(iv) The residual ratios of dynamic Young's modulus for concrete test specimens cooled from 250°C and immersed in water for 7 days before testing range between 80% and 90%. The corresponding residual ratios for mortar test specimens are always lower than those for the concrete test specimens, and range from 68% to 76%. For both the concrete specimens and the mortar specimens the residual ratios are 25% to 40% greater than those for the corresponding specimens tested immediately after cooling from 250°C.

(v) Test specimens which were cooled from 400°C and immersed in water for 7 days before testing have residual ratios which differ widely for the three concrete mixes as well as for the three mortar mixes. The concrete mixes BCY and CCY have residual ratios of dynamic Young's modulus which range between 78% and 91% whereas the residual ratios of the concrete mix CCX range from 65% to 70%. The residual ratios of dynamic Young's modulus for the various mortar mixes exhibit still greater scatter, viz. the residual ratios of the mortar mixes BMY, CMX and CMY were between 85% and 95%, 72% and 80%, and 63% and 67%, respectively. All the above residual ratios are approximately 50% greater than the residual ratios of the corresponding test specimens which were tested immediately after cooling from 400°C.

The residual ratios of dynamic Young's modulus for specimens which remained fully saturated during heating and were cooled and re-immersed in water for 7 days before testing, are also shown in Figure III.34, Figure III.36 and Figure III.38. Both concrete and mortar test specimens cooled from 70°C before testing, exhibit reductions in dynamic Young's modulus which are usually not greater than 10%. The reductions in dynamic Young's modulus for specimens which were heated to 100°C are between 10% and 25%. At both 70°C and 100°C the concrete specimens exhibit approximately the same reductions as the corresponding mortar specimens. Furthermore, these reductions appear to be approximately the same as those which occurred for saturated specimens which were tested immediately after cooling from these temperature levels.

4.3 The Dynamic Young's modulus of Test Specimens which were Subjected to Temperature Cycling

The residual ratios of dynamic Young's modulus for test specimens which were subjected to temperature cycling are illustrated in Figure III.39 to Figure III.44. Figure III.39 shows the residual ratios for the concrete mix BCY and the mortar mix BMY, Figure III.41 the residual ratios for mixes CCX and CMX, and Figure III.43 the residual ratios for mixes CCY and CMY; all these data refer to tests performed immediately after specimens had cooled to the datum temperature. Figure III.40, Figure III.42 and Figure III.44 show the residual ratios for test specimens which were immersed in water for 7 days after cooling.

It is apparent that these data closely resemble the data obtained for test specimens which were not subjected to temperature cycling. In many instances

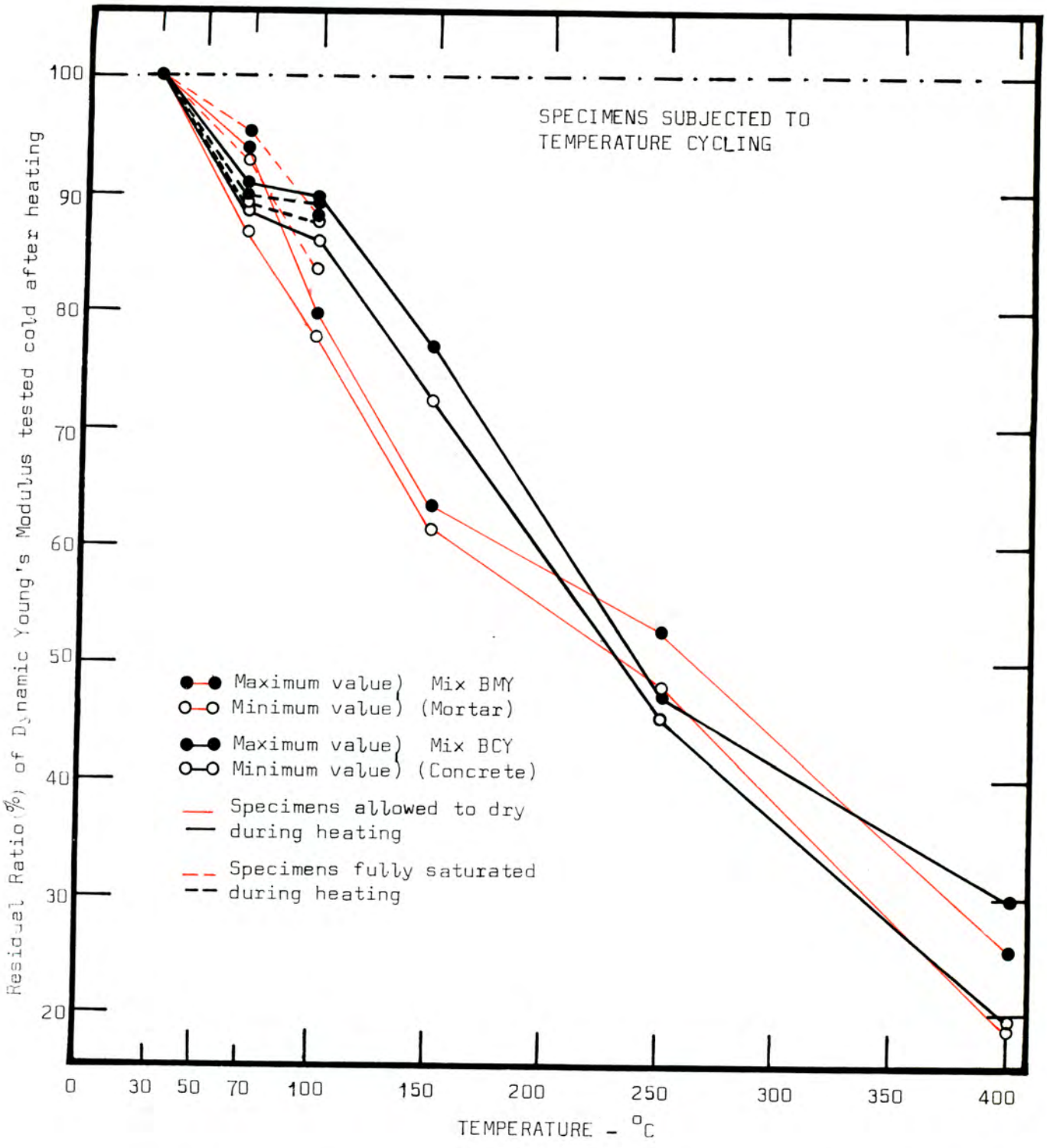


FIG.III.39: The residual ratio (%) of dynamic Young's Modulus for specimens tested after cooling : Mixes BCY and BMY.

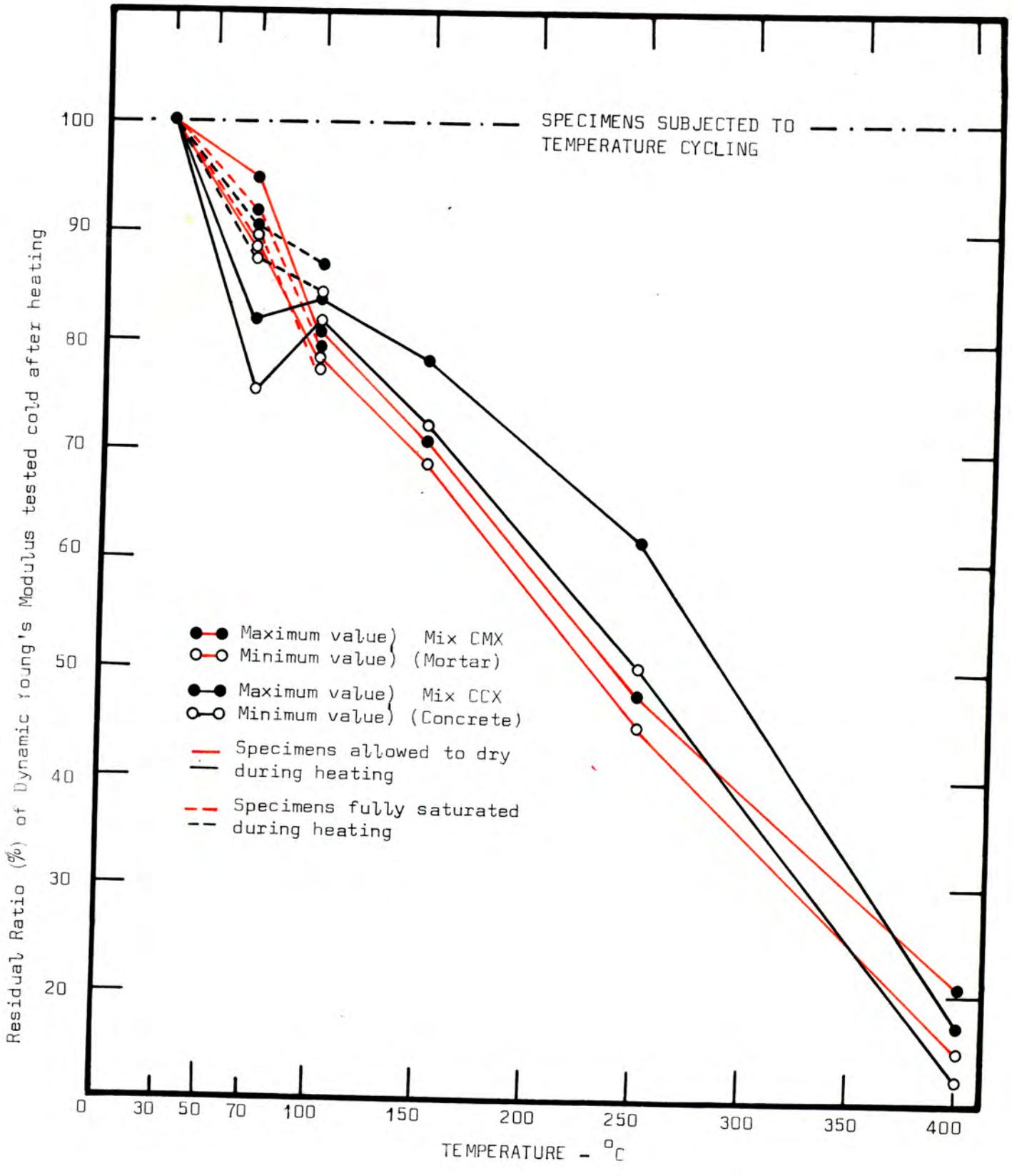


FIG.III.41: The residual ratio (%) of dynamic Young's Modulus for specimens tested after cooling : Mixes CCX and CMX.

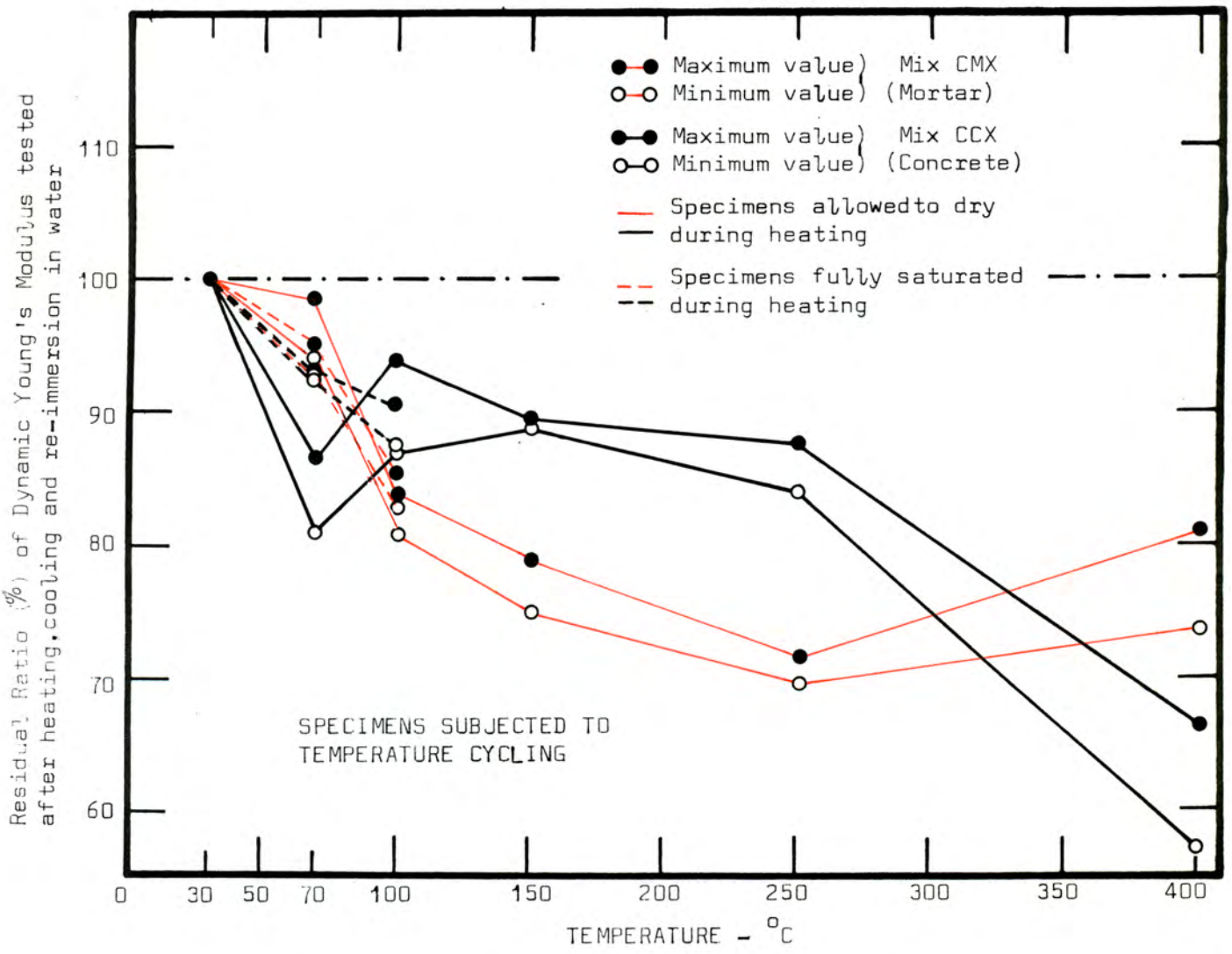


FIG.III.42: The residual ratio (%) of dynamic Young's Modulus for specimens tested after re-immersion in water : Mixes CCX and CMX.

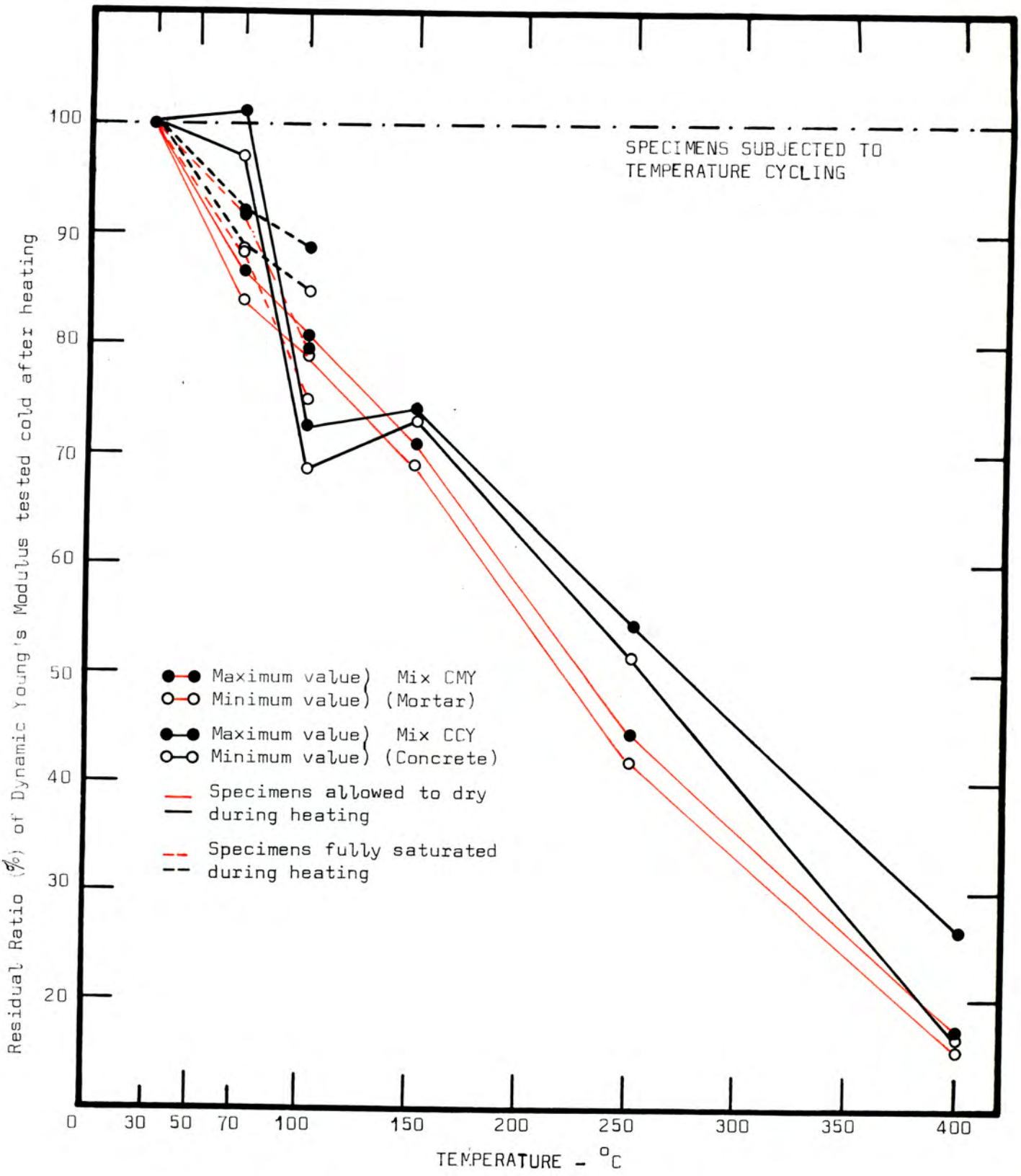


FIG.III.43: The residual ratio (%) of dynamic Young's Modulus for specimens tested after cooling : Mixes CCY and CMY

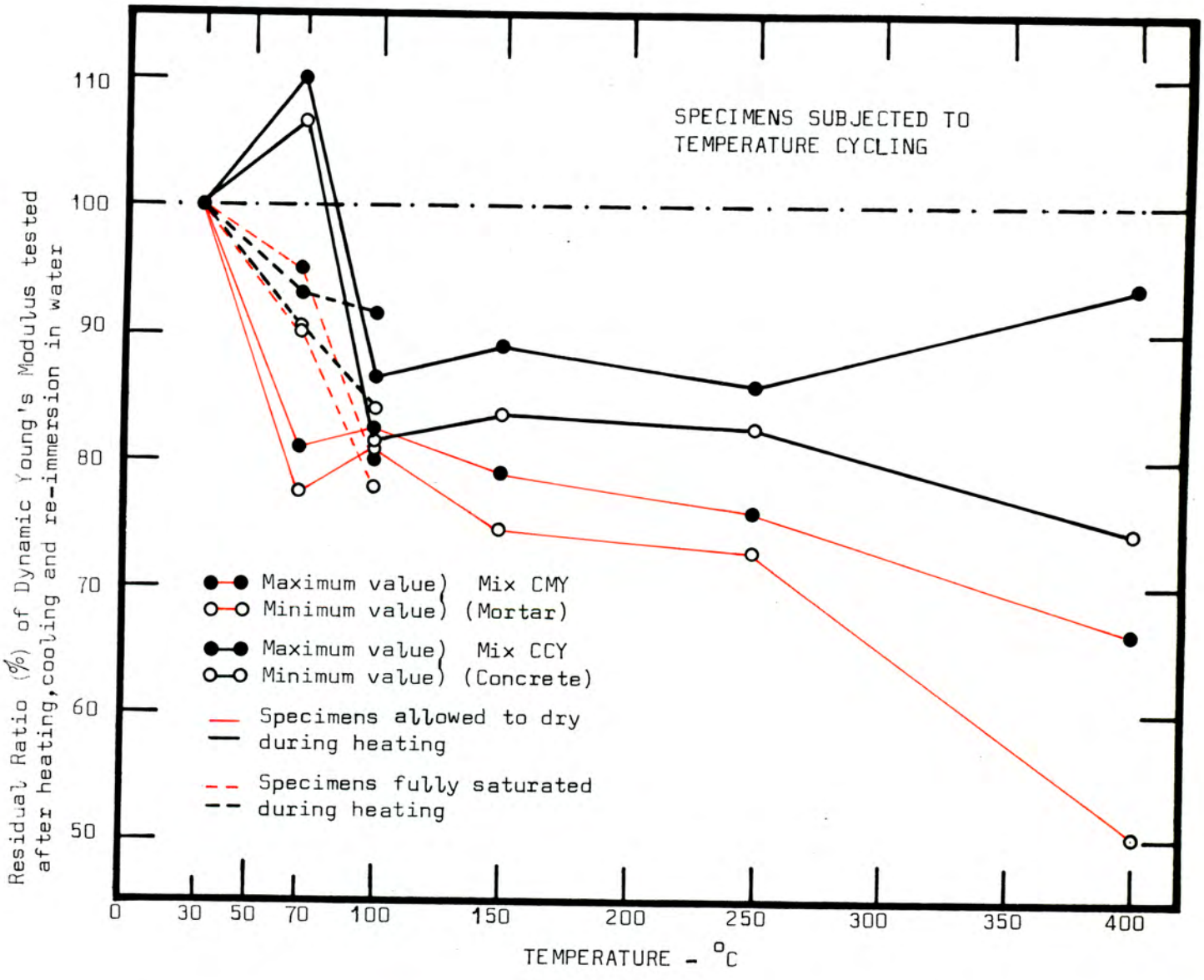


FIG.III.44: The residual ratio (%) of dynamic Young's Modulus for specimens tested after re-immersion in water : Mixes CCY and CMY.

the residual ratios of dynamic Young's modulus for test specimens which were subjected to temperature cycling are almost identical to the residual ratios for test specimens not subjected to temperature cycling. There are wide variations between the residual ratios of dynamic Young's modulus for specimens made from the various concrete mixes (as well as for specimens made from the various mortar mixes), but the variations between the mixes occur at the same temperature levels as the variations which occurred for the concrete mixes and mortar mixes not subjected to temperature cycling. Consequently, it appears that the various concrete mixes, as well as the various mortar mixes, exhibit significantly different behaviour at certain temperature levels and that the observed variations between mixes are not due to experimental error.

A statistical analysis which elucidates the effect of heating time and temperature cycling on the dynamic Young's modulus is given in PART IV : STATISTICAL ANALYSIS.

CHAPTER 5 : POISSON'S RATIO OF CONCRETE AND MORTAR SPECIMENS SUBJECTED TO HEATING

Poisson's ratio was calculated for all the test specimens on which ultrasonic pulse velocity and dynamic Young's modulus were determined. The method of calculating Poisson's ratio is given in APPENDIX 1.2. The calculated values of Poisson's ratio are shown in APPENDIX II, Table A.II.1 to Table A.II.42. For each of the various concrete and mortar mixes the mean value of Poisson's ratio was calculated from the values of Poisson's ratio for unheated (control) specimens. The mean values for the various concrete and mortar mixes are given in CHAPTER 1 : PROPERTIES OF THE HARDENED CONCRETE AND MORTAR MIXES. The residual ratio of Poisson's ratio for heated specimens was calculated by dividing Poisson's ratio of a heated specimen by the mean control value of Poisson's ratio for test specimens of that particular mix.

5.1 Poisson's Ratio of Concrete and Mortar Specimens determined from Tests Immediately after Test Specimens had Cooled from the Test Temperatures

The maximum residual ratios and minimum residual ratios for Poisson's ratio of test specimens cooled from the various temperature levels are illustrated in Figure III.45, Figure III.47 and Figure III.49 for mixes BCY and BMY, mixes CCX and CMX, and mixes CCY and CMY, respectively. The data for specimens which underwent drying during heating as well as the data for test specimens which remained fully saturated during heating are shown. The maximum and minimum residual ratios shown in these figures do not include the values determined on test specimens subjected to temperature cycling.

The data shown in Figure III.45, Figure III.47 and Figure III.49 for test specimens which underwent drying during heating, indicate that:

(i) At all temperature levels, the percentage change in Poisson's ratio of mortar test specimens differs from the percentage change in Poisson's ratio of concrete test specimens. Furthermore, at some temperature levels the value of Poisson's ratio for concrete specimens is greater than the mean control value of Poisson's ratio whereas for mortar specimens the value of Poisson's ratio is less than the mean control value. It is particularly noticeable, too, that in some instances there are large variations between the maximum and the minimum residual ratios of Poisson's ratio for specimens of a particular mix tested at

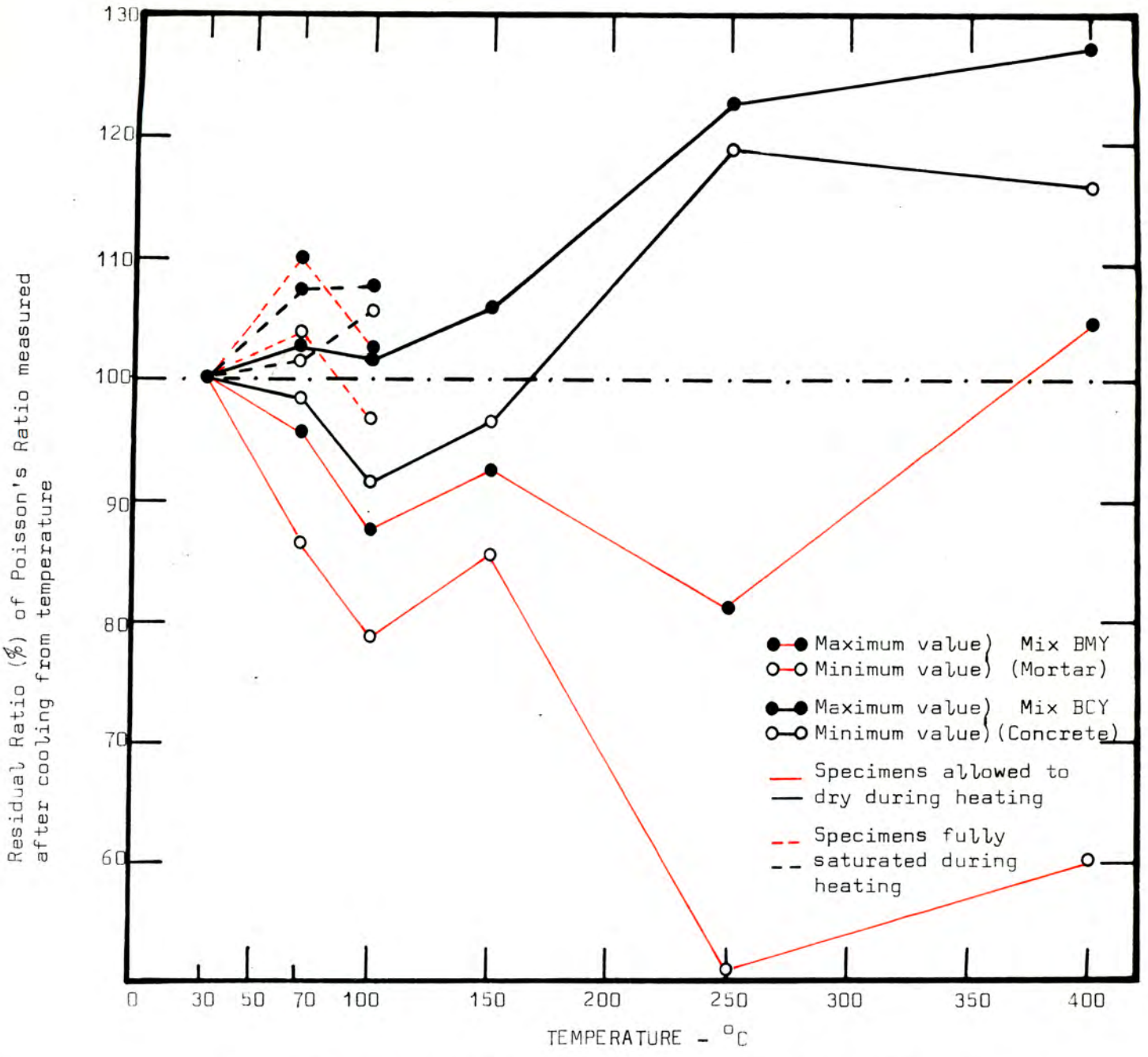


FIG.III.45: The residual ratio (%) of Poisson's Ratio for specimens tested after cooling : Mixes BCY and BMY.

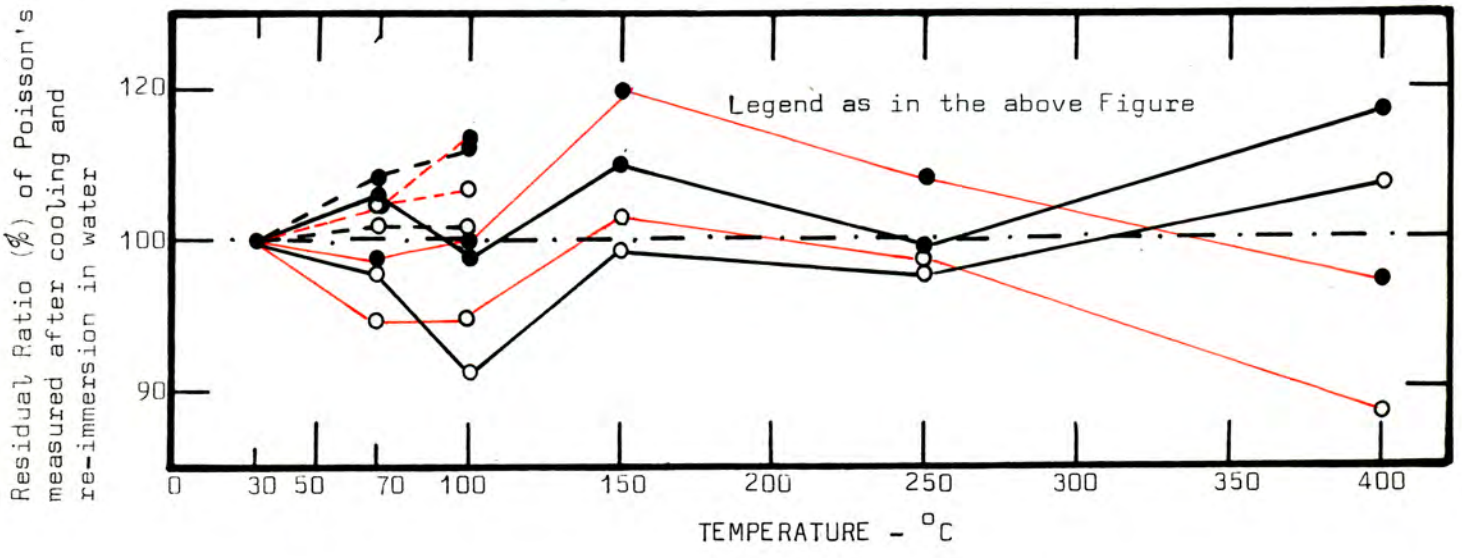


FIG.III.46: The residual ratio (%) of Poisson's Ratio for specimens tested after re-immersion in water : Mixes BCY and BMY.

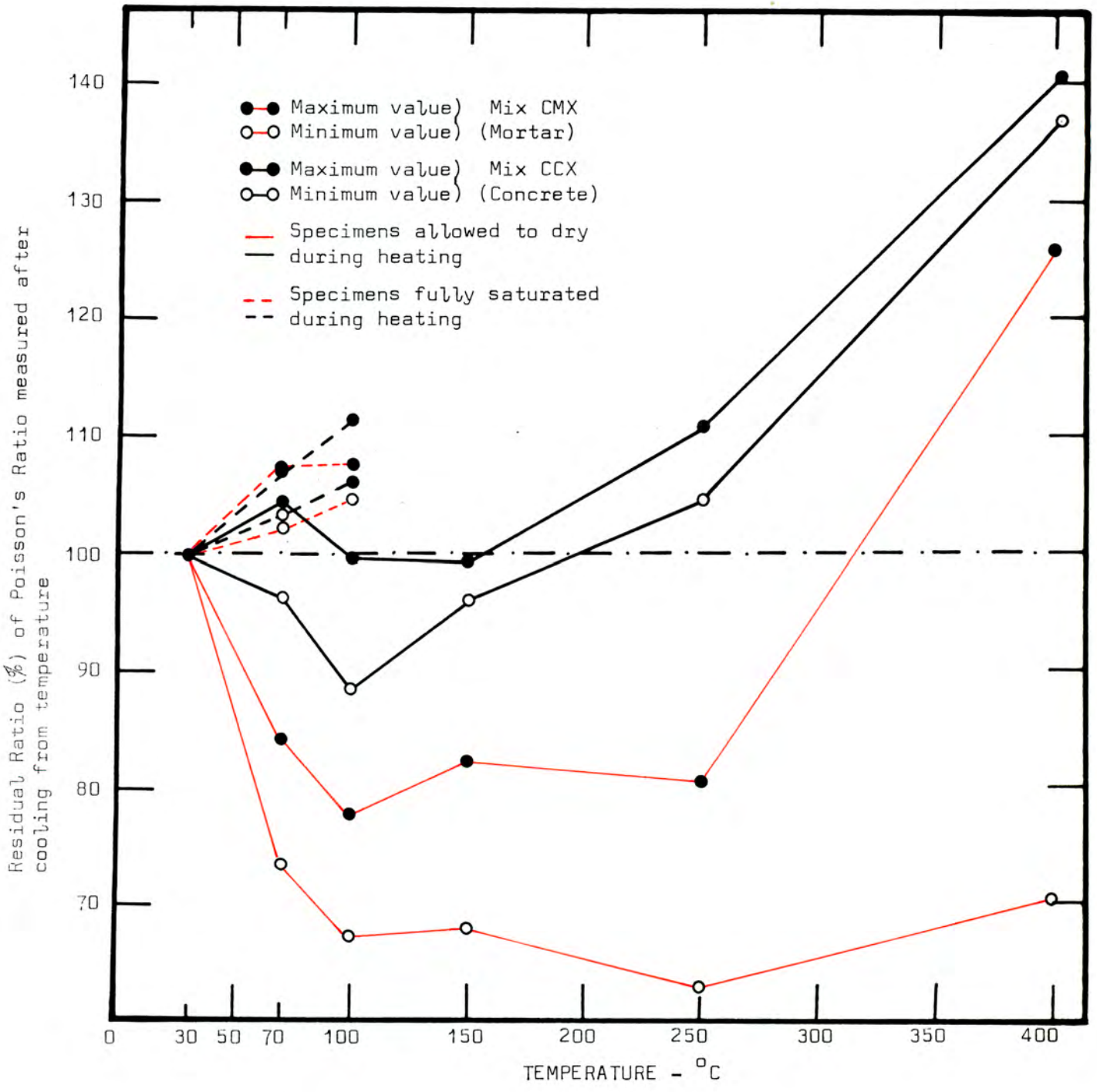


FIG.III.47: The residual ratio (%) of Poisson's Ratio for specimens tested after cooling : Mixes CCX and CMX.

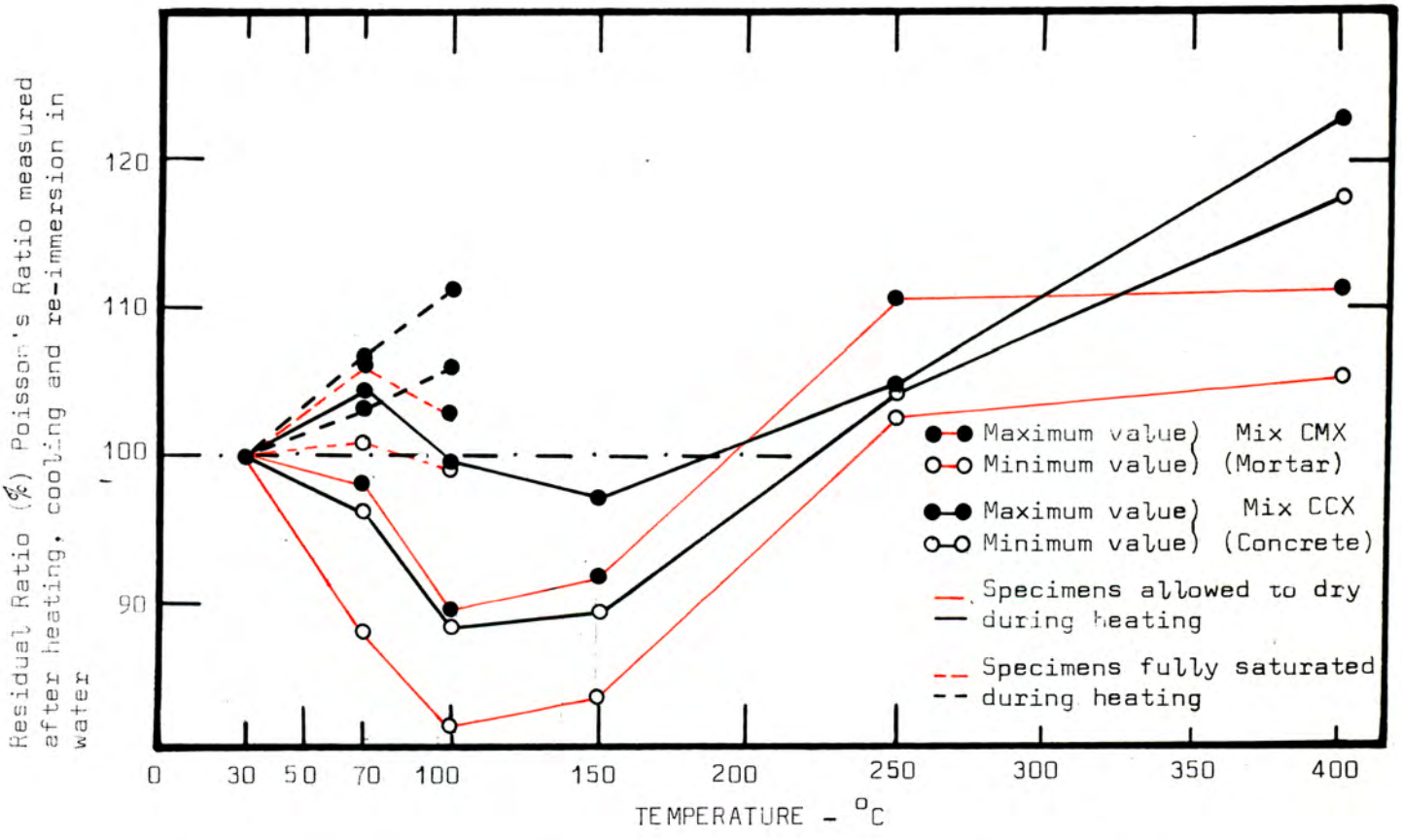


FIG.III.48: The residual ratio (%) of Poisson's Ratio for specimens tested after re-immersion in water : Mixes CCX and CMX.

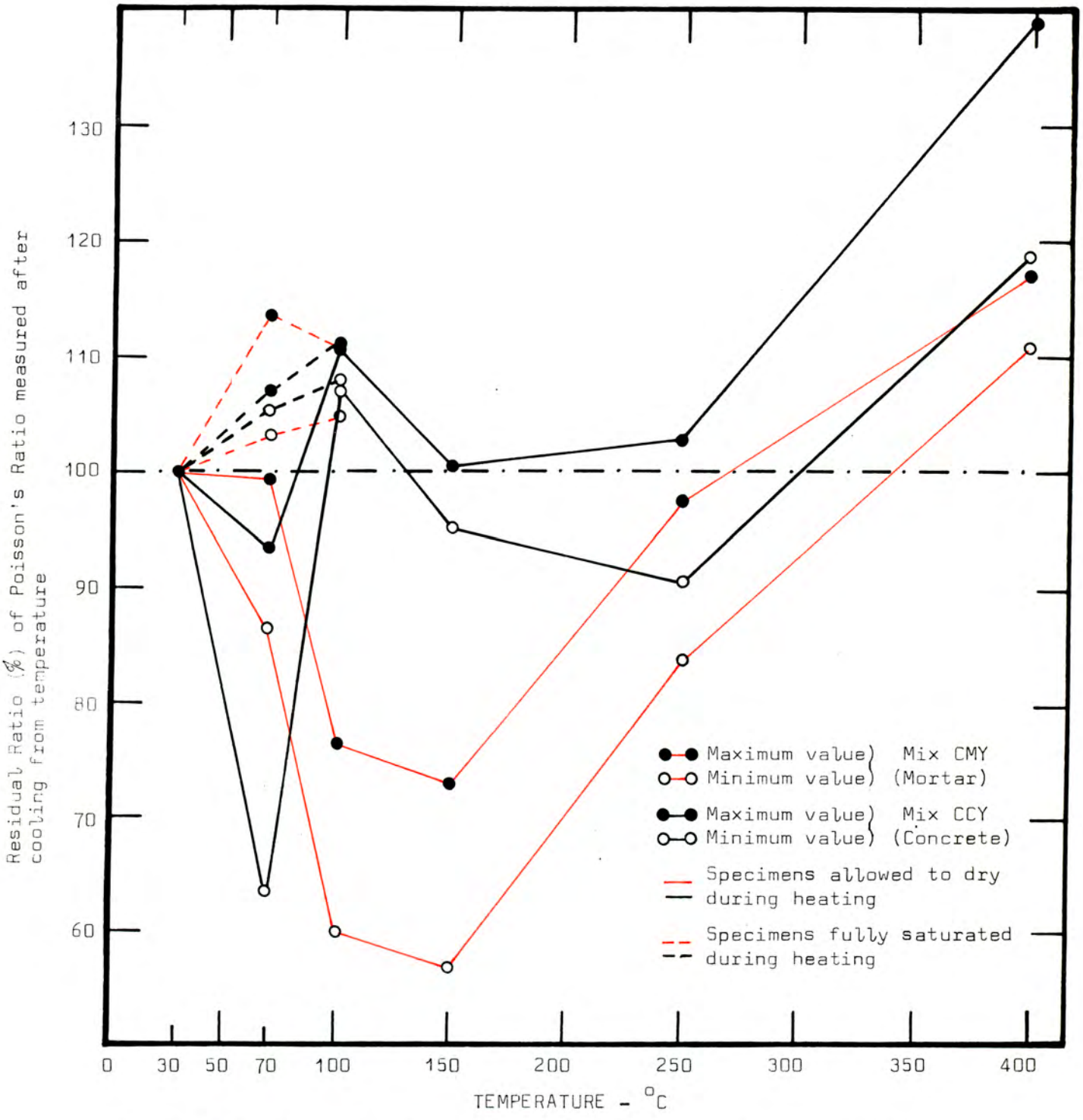


FIG.III.49: The residual ratio (%) of Poisson's ratio for specimens tested after cooling : Mixes CCY and CMY.

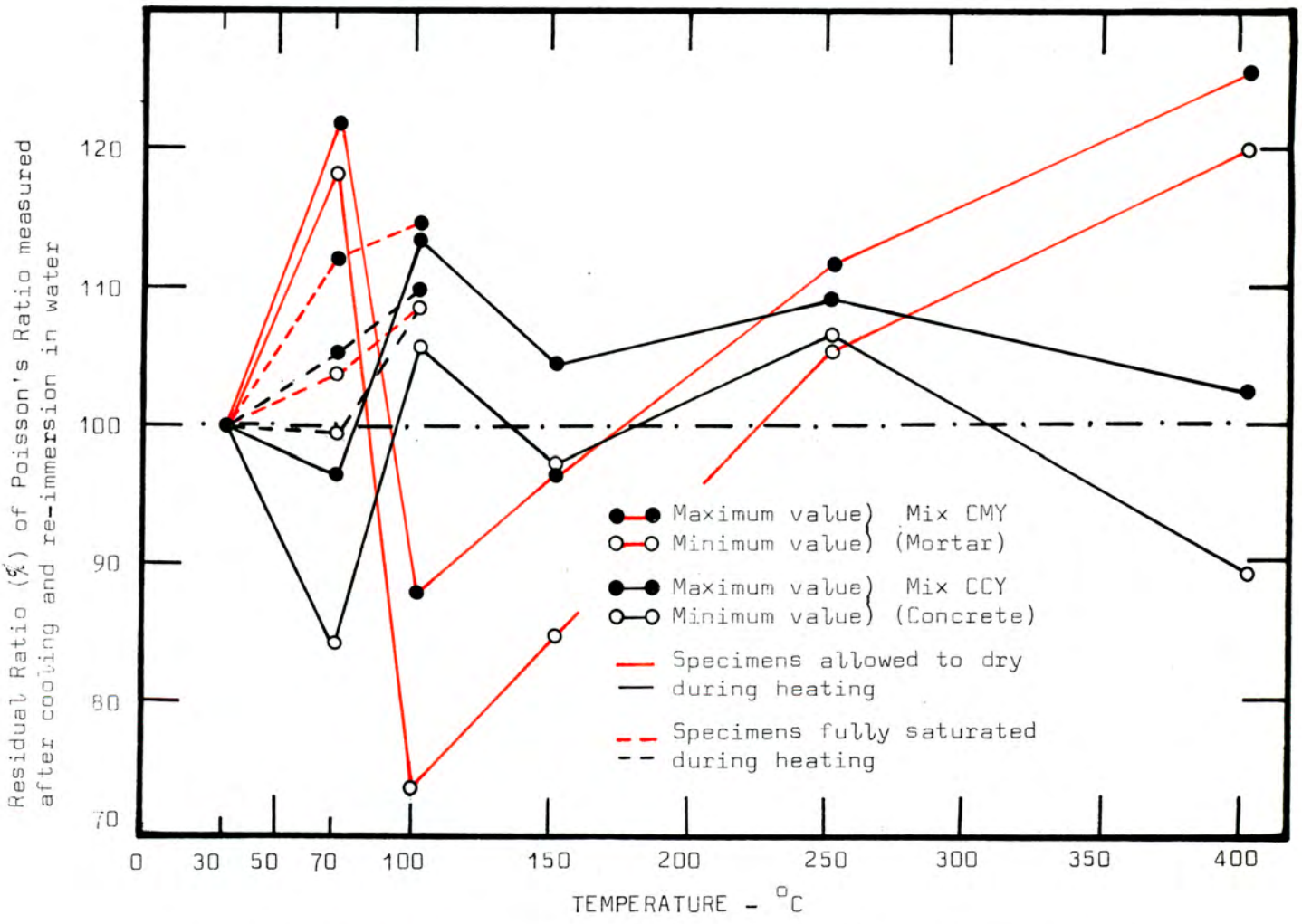


FIG.III.50: The residual ratio (%) of Poisson's Ratio for specimens tested after re-immersion in water : Mixes CCY and CMY.

a particular temperature, e.g. for the mortar mix CMX the difference between the maximum and the minimum residual ratio is approximately 55% for test specimens cooled from 400°C.

(ii) Test specimens cooled from 70°C exhibit residual ratios of Poisson's ratio which range between 96% and 106% for the two concrete mixes BCY and CCX, and between 64% and 94% for the concrete mix CCY. The residual ratios for the mortar specimens cooled from 70°C also differ widely between mixes, e.g. the residual ratios for mix BMY range from 86% to 96%, those for mix CMX range from 75% to 84% and the residual ratios for mix CMY range from 86% to 100%.

(iii) The residual ratios of test specimens cooled from 100°C range between 89% and 102% for test specimens made from the concrete mixes BCY and CCX, whereas the residual ratios for the concrete mix CCY range from 107% to 111%. The residual ratios of test specimens made from the mortar mixes BMY, CMX and CMY are between 79% and 88%, 67% and 78%, and 60% and 76%, respectively. For the mortar test specimens the residual ratio of Poisson's ratio at 100°C was always smaller than that at 70°C.

(iv) The residual ratios of Poisson's ratio for test specimens cooled from 150°C are approximately the same for the three different concrete mixes. Values of the residual ratio range between 95% and 106%. For the mortar mixes, however, the residual ratios exhibit a similar trend to the residual ratios of mortar specimens cooled from 100°C, i.e. the residual ratios of the various mortar mixes differ widely and range from 85% to 93% for mix BMY, 68% to 82% for mix CMX and 57% to 73% for mix CMY.

(v) Test specimens cooled from 250°C exhibit residual ratios of Poisson's ratio which range between 90% and 123% for specimens made from the various concrete mixes. The residual ratios for the mortar mixes range from 51% to 98%, for mixes BMY and CMX they are between 51% and 81% whereas the residual ratios for specimens of mix CMY range from 85% to 98%.

(vi) The residual ratios of Poisson's ratio for test specimens cooled from 400°C are always greater than the residual ratios for specimens cooled from 250°C. The residual ratios for the concrete mixes BCY, CCX and

CCY were from 116% to 128%, 137% to 142% and 119% to 139% respectively. For mortar test specimens the residual ratios were between 60% and 105% for mix BMY, between 70% and 125% for mix CMX and between 110% and 117% for mix CMY.

Test specimens which remained fully saturated at temperatures of either 70°C or 100°C usually exhibit values of Poisson's ratio which are larger than the values for unheated test specimens. At 70°C the residual ratios range between 101% and 113%. It appears that at this temperature level the concrete and mortar specimens undergo similar changes in Poisson's ratio. The residual ratios of Poisson's ratio for saturated test specimens cooled from 100°C range from 96% to 111%. At both 70°C and 100°C the residual ratios of Poisson's ratio for test specimens which remained saturated during heating are usually greater than the residual ratio for specimens which underwent drying during heating.

5.2 Poisson's Ratio of Specimens which were Cooled and Immersed in Water for 7 Days Before Testing

The maximum residual ratio and minimum residual ratio of Poisson's ratio for test specimens which were cooled and immersed in water for 7 days before testing, are shown in Figure III.46, Figure III.48 and Figure III.50. Figure III.46 illustrates the data for the concrete mix BCY and the corresponding mortar mix BMY, Figure III.48 the data for mixes CCX and CMX, and Figure III.50 the residual ratio for mixes CCY and CMY. The residual ratios shown in the above-mentioned diagrams do not include values determined on test specimens subjected to temperature cycling.

From Figure III.46, Figure III.48 and Figure III.50 it is apparent that for specimens which were allowed to dry during heating:

(i) The difference between the maximum and minimum residual ratio of Poisson's ratio for both concrete and mortar test specimens at the various temperature levels is not as great as the difference which occurred for the corresponding test specimens which were tested immediately after cooling. Furthermore, for specimens which were cooled and immersed in water for 7 days before testing, the residual ratio of Poisson's ratio for specimens made from the concrete mixes do not differ as markedly from the residual ratio of Poisson's ratio for specimens made from the mortar mixes, as was the case for specimens which were tested immediately after cooling.

(ii) Concrete test specimens which were cooled from 70°C and immersed in water for 7 days before testing exhibit residual ratios which are in some instances exactly similar to the residual ratios of the corresponding test specimens which were tested immediately after cooling. This occurred for the concrete mixes BCY and CCX; the residual ratios ranged between 96% and 104%. However, the residual ratios of Poisson's ratio for the concrete mix CCY are greater than those found for specimens tested immediately after cooling. These values ranged from 84% to 97%. Mortar test specimens which were cooled from 70°C and immersed in water for 7 days before testing always exhibit greater residual ratios of Poisson's ratio than the corresponding mortar specimens which were tested immediately after cooling from 70°C. The residual ratios ranged from 95% to 99% for the mortar mix BMY, from 88% to 98% for mix CMX, and from 118% to 122% for mix CMY.

(iii) Concrete test specimens cooled from 100°C and immersed in water for 7 days before testing always have residual ratios of Poisson's ratio which are approximately the same as those found for the corresponding concrete specimens which were tested immediately after cooling from 100°C. For the concrete mixes BCY, CCX and CCY the residual ratios were from 91% to 99%, 88% to 99%, and 106% to 113%, respectively. The mortar mixes exhibit residual ratios of between 95% and 100% for mix BMY, between 82% and 90% for mix CMX, and between 75% and 88% for mix CMY. These values are approximately 10% higher than the residual ratios of Poisson's ratio of mortar specimens which were tested immediately after cooling.

(iv) The residual ratios of Poisson's ratio for concrete test specimens cooled from 150°C and immersed in water for 7 days before testing range between 90% and 105% for the various concrete mixes. This range of residual ratios is approximately the same as the range of residual ratios for specimens tested immediately after cooling. Mortar test specimens which were cooled from 150°C and immersed in water for 7 days before testing have residual ratios which range between 93% and 110%. In some instances these values are 25% greater than the residual ratios of Poisson's ratio for mortar specimens which were tested immediately after cooling from 150°C

(v) Concrete test specimens cooled from 250°C and immersed in water for 7 days before testing have residual ratios of Poisson's ratio which are very similar to the residual ratios of Poisson's ratio for mortar

specimens which were subjected to similar treatment. The residual ratios of all the concrete and mortar mixes were between 98% and 111%. The residual ratios for specimens from the various mortar mixes were always greater than the residual ratios for the corresponding mortar specimens which were tested immediately after cooling. For specimens made from the various concrete mixes the residual ratios do not exhibit a similar trend.

(vi) Test specimens cooled from 400°C and tested after 7 days in water do not exhibit as large a difference between the maximum residual ratio and minimum residual ratio of Poisson's ratio as specimens which were tested immediately after cooling. However, both the concrete and the mortar mixes exhibit widely different residual ratios between mixes. The residual ratios for the concrete mixes BCY, CCX and CCY ranged between 104% and 109%, 117% and 123%, and 89% and 103%, respectively. For the mortar mixes BMY, CMX and CMY, the residual ratios were between 88% and 98%, 105% and 111%, and 120% and 126%, respectively.

Test specimens which remained fully saturated during heating at 70°C and were cooled and kept in water for 7 days before testing, have residual ratios of Poisson's ratio which range between 100% and 112%. It appears that the concrete and mortar specimens exhibit approximately similar residual ratios. Furthermore, these residual ratios fall within the same range as the residual ratios of test specimens which remained fully saturated at 70°C and were tested immediately after cooling from this temperature level. The residual ratios of saturated specimens cooled from 100°C and tested after 7 days in water range between 99% and 114%. These values, too, are approximately similar to the residual ratios of saturated specimens tested immediately after cooling from 100°C.

The results in section 3.3.1 and section 3.3.2 clearly illustrate that for a particular mix, test specimens which were tested at different times during the heating period may have widely different values for Poisson's ratio. This is particularly noticeable at test temperatures above 150°C. The variation between the maximum and minimum residual ratio could be due to either:

(i) Time dependent changes in the Poisson's ratio of test specimens during the heating period. These changes could be related to the water loss

of test specimens since it was found that at all temperature levels the test specimens lose water throughout the heating period. (Water loss is discussed in CHAPTER 6 : THE WATER LOSS OF CONCRETE AND MORTAR SPECIMENS DURING HEATING.)

(ii) Internal microcracking of the test specimens. This affects the accuracy with which the resonant frequency for determining the dynamic Young's modulus can be measured, i.e. resonance occures over a relatively large frequency range. Since a 1% error in resonant frequency may result in a 20% error in Poisson's ratio, it is apparent that this effect may have been highly significant.

The results for Poisson's ratio of heated specimens indicate, too, that the different concrete mixes (and the different mortar mixes) may exhibit widely different residual ratios when heated. These variations are also apparent for test specimens which were subjected to temperature cycling. The residual ratios of Poisson's ratio are shown in Figure III.51, Figure III.53 and Figure III.55 for test specimens which underwent temperature cycling and were tested immediately after cooling, and in Figure III.52, Figure III.54 and Figure III.56 for test specimens which underwent temperature cycling and were cooled and immersed in water for 7 days before testing. From these results it is apparent that in many instances the variations between the concrete mixes, as well as those between the mortar mixes, are similar to the variations which occurred for test specimens not subjected to temperature cycling. This data indicates, too, that in some instances the difference between the maximum residual ratio and the minimum residual ratio is even greater than the difference which occurred for test specimens not subjected to temperature cycling. Consequently, it appears that at certain temperature levels some further change in Poisson's ratio does occur when test specimens are subjected to temperature cycling.

A statistical analysis of these results is given in PART IV - STATISTICAL ANALYSIS.

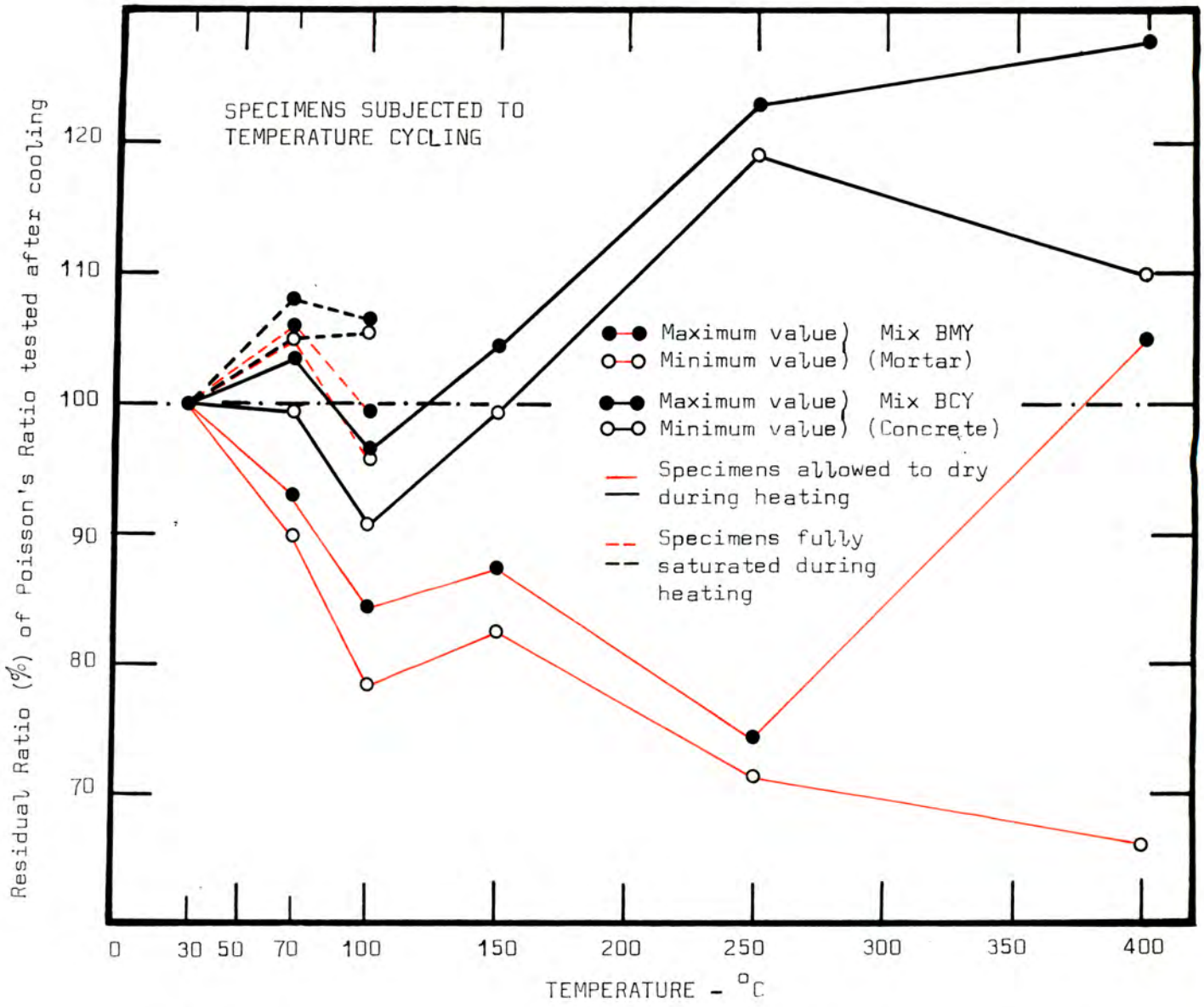


FIG.III.51: The residual ratio (%) of Poisson's Ratio for specimens tested after cooling : Mixes BCY and BMY.

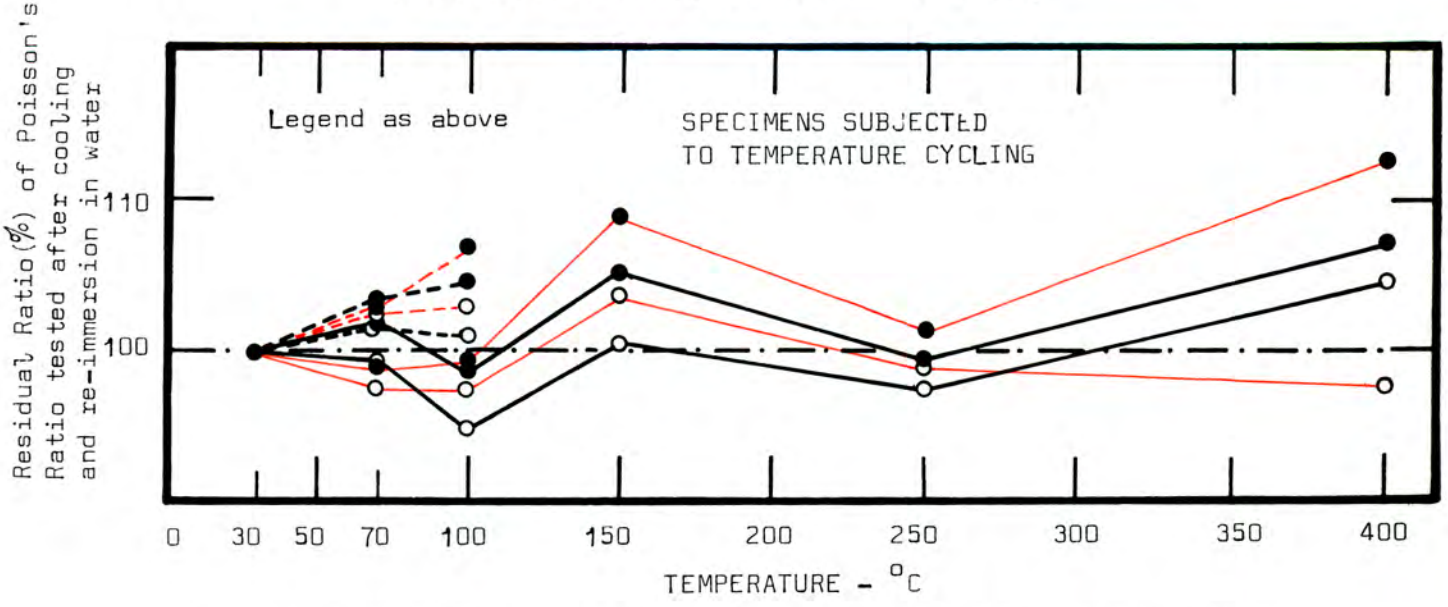


FIG.III.52: The residual ratio (%) of Poisson's Ratio for specimens tested after re-immersion in water : Mixes BCY and BMY.

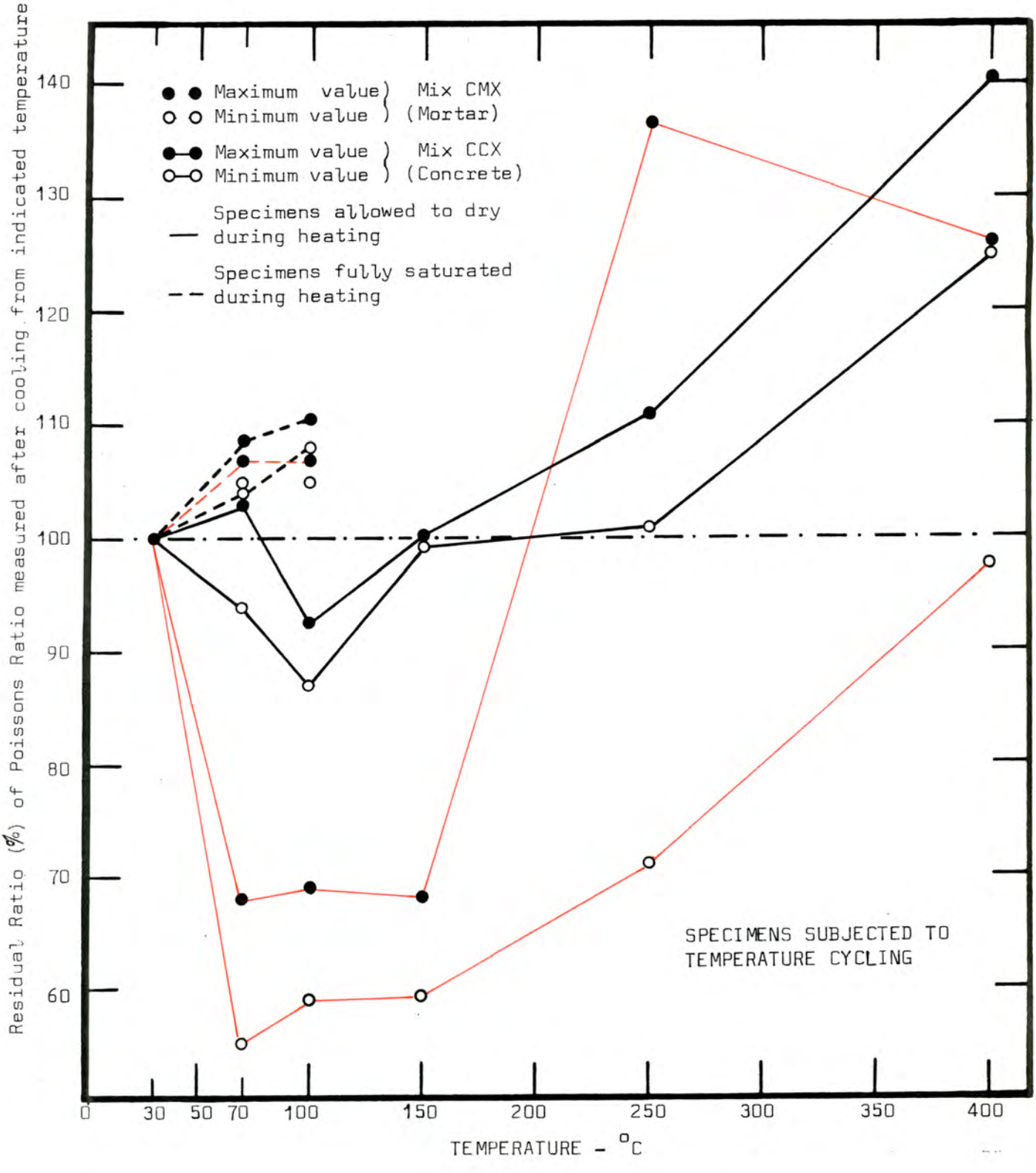


FIG.III.53: The residual ratio (%) of Poisson's Ratio for specimens tested after cooling : Mixes CCX and CMX.

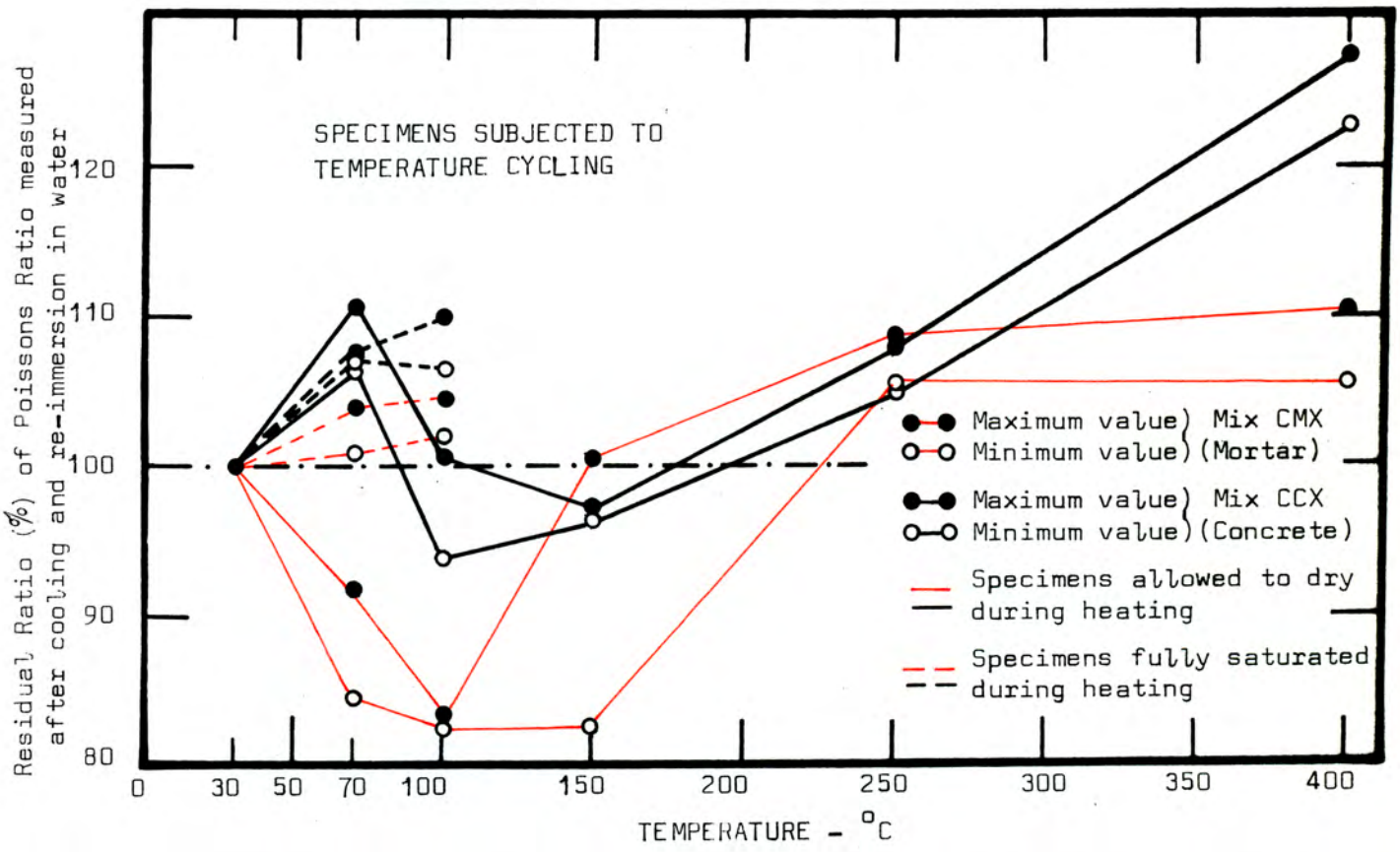


FIG.III.54: The residual ratio (%) of Poisson's Ratio for specimens tested after re-immersion in water : Mixes CCX and CMX.

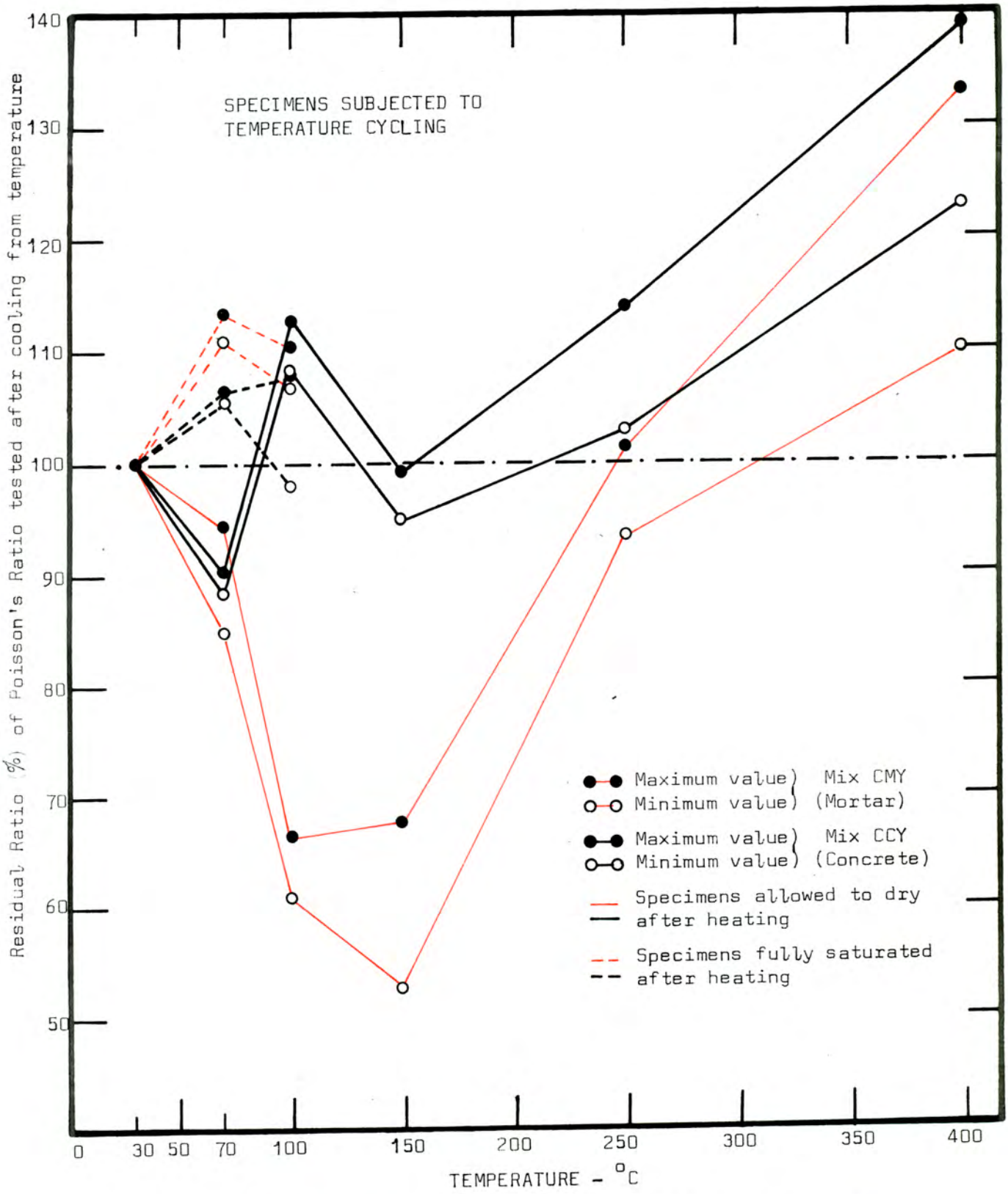


FIG.III.55: The residual ratio (%) of Poisson's Ratio for specimens tested after cooling : Mixes CCY and CMY.

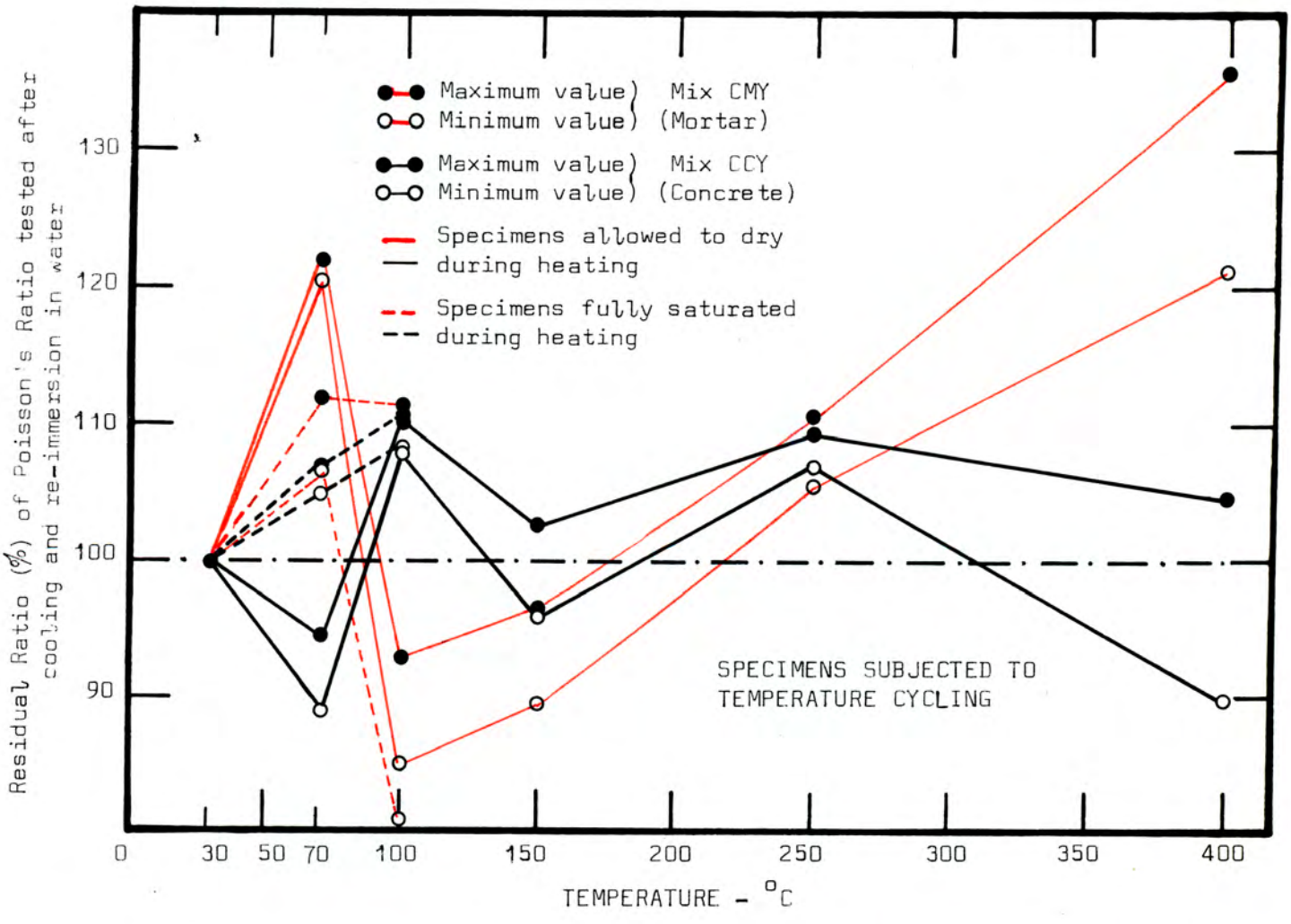


FIG.III.56: The residual ratio (%) of Poisson's Ratio for specimens tested after re-immersion in water : Mixes CCY and CMY.

CHAPTER 6 : THE WATER LOSS OF CONCRETE AND MORTAR TEST SPECIMENS DURING HEATING

The water loss was determined for specimens which underwent drying at temperatures of 70°C, 100°C, 150°C, 250°C and 400°C respectively. For a particular mix tested at any of the abovementioned temperature levels the water loss was measured;

(i) continuously on one specimen during the heating period (in Furnace No. 1), and

(ii) on the test specimens which were removed from Furnace No. 2 at the various times during the heating period and allowed to cool before weighing.

The water loss is expressed as a percentage of the total amount of water (W_t) contained in the test specimen prior to heating. The method of calculating W_t is given in APPENDIX I.4. Also shown in APPENDIX I.4 is the method of calculating the capillary water content (W_c), the water in the gel pores (W_g) and the chemically combined water (W_n). The calculated values of W_c, W_g and W_n, expressed as a percentage of W_t, are shown in Table III.5 for the various concrete and mortar mixes.

TABLE III.5

The percentage of capillary water (W_c), water in the gel pores (W_g) and chemically combined water (W_n) for the various concrete and mortar mixes

	MIX NAME	W_n (%)	W_c (%)	W_g (%)
CONCRETE MIXES	BCY	30,6	44,1	25,3
	CCX	26,6	51,5	22,0
	CCY	26,6	51,5	21,9
MORTAR MIXES	BMY	30,5	44,3	25,2
	CMX	26,7	51,3	22,0
	CMY	26,6	51,3	22,1

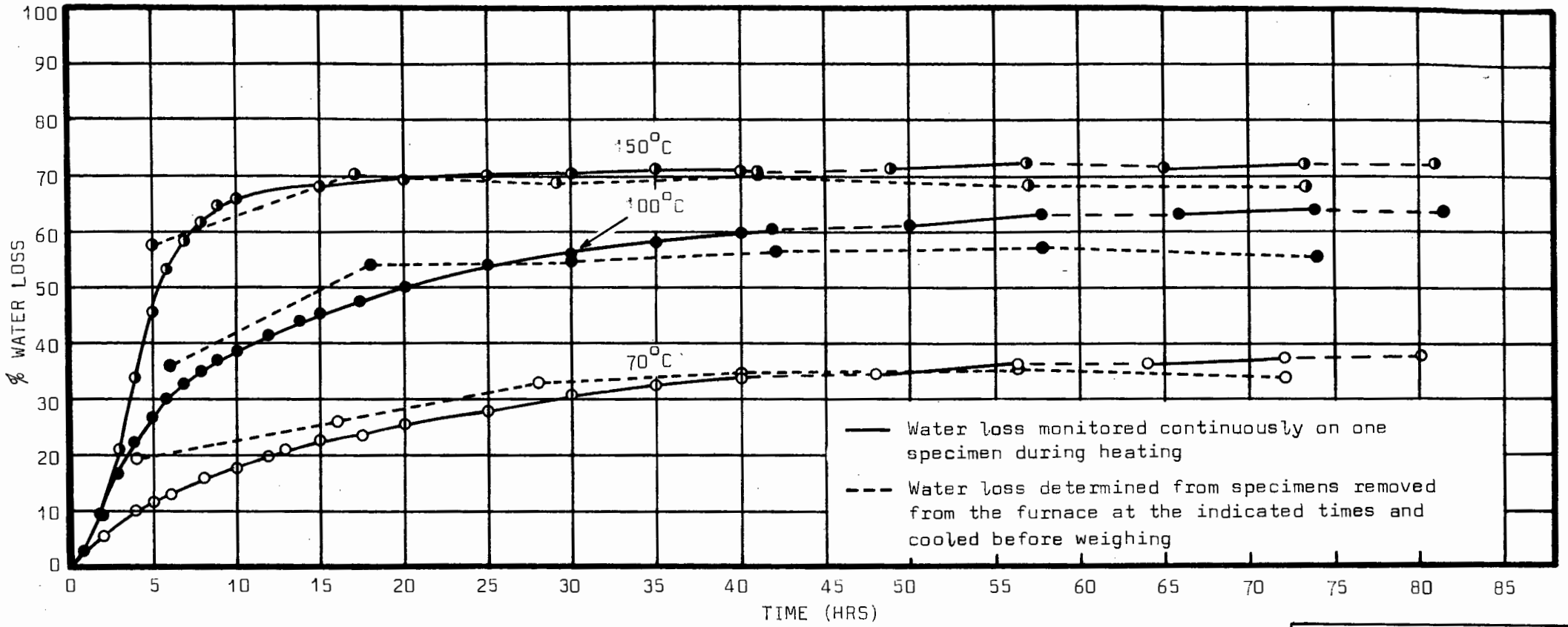
The results obtained from continuous measurement of water loss during the heating period are given in APPENDIX III, Figure A.III.1 to Figure A.III.12. In each figure the numerical values of water loss are tabulated below the plotted values. Some typical water loss curves similar to those shown in APPENDIX III are illustrated in Figure III.57, Figure III.58, Figure III.59 and Figure III.60. Figure III.57 shows the water loss of the concrete test specimens of mix BCY at temperatures of 70°C, 100°C and 150°C, and Figure III.58 the water loss of these specimens at 250°C and 400°C. Figure III.59 and Figure III.60 illustrate the data for the corresponding mortar mix BMY.

The water loss of test specimens which were removed from Furnace No. 2 at the various times during the heating period are given in APPENDIX II, Table A.II.1 to Table A.II.42. These water loss values are plotted on the same figure as the data obtained from the continuous water loss determinations, viz. Figure III.57 to Figure III.60, and Figure A.III.1 to Figure A.III.12 in APPENDIX III.

From the abovementioned results it is apparent that there is usually good agreement between the water loss of the specimens which were allowed to cool before weighing and the water loss which was measured continuously on a test specimen whilst hot. However, at temperatures of 70°C and 100°C, and in some instances at 150°C, the specimens which were cooled before weighing exhibit greater water loss than the specimen on which the water loss was determined whilst hot. This indicates that an appreciable water loss occurred during cooling of these test specimens, particularly for test specimens which were removed from the furnace immediately the desired temperature level had been attained.

The data obtained from test specimens on which the water loss was continuously monitored indicate that:

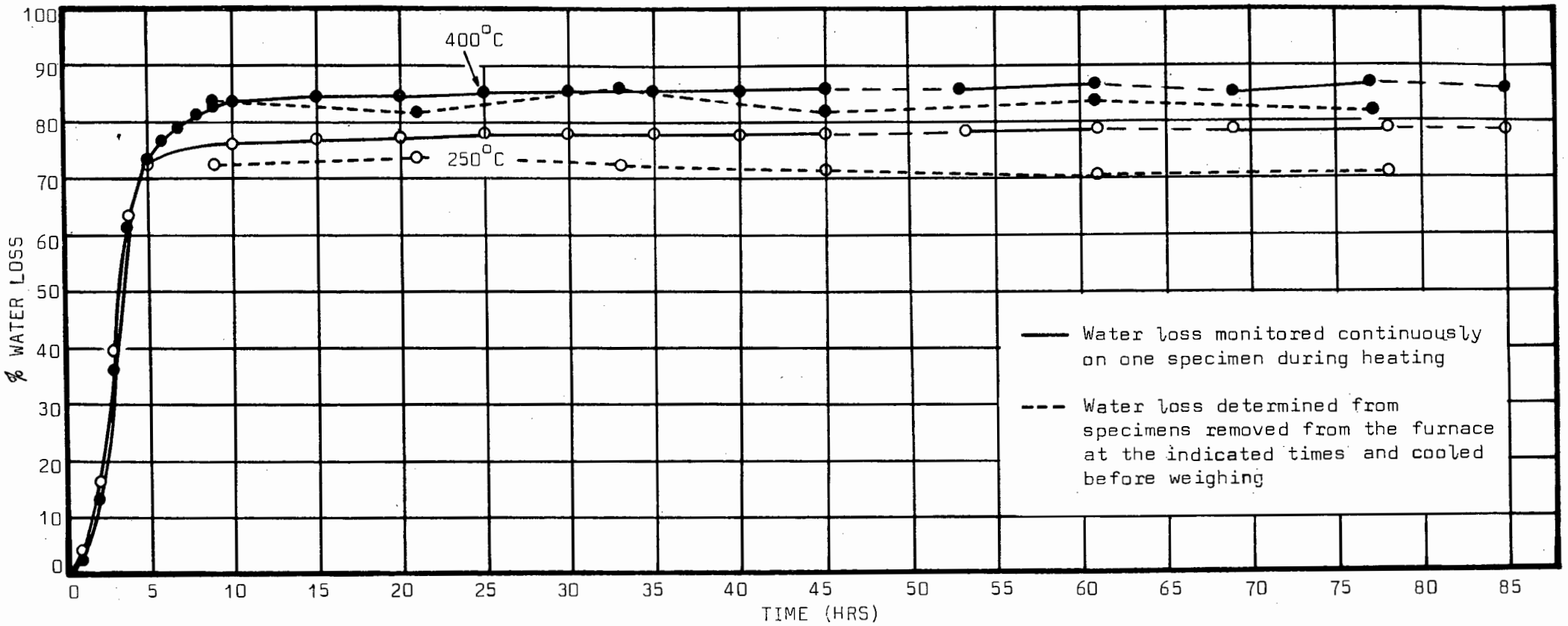
(i) There is usually good agreement between the percentage water loss of concrete test specimens and the percentage water loss of the corresponding mortar test specimens. In Table III.6 the percentage water loss of test specimens made from the various concrete and mortar mixes are shown. The water loss values shown are those at 40 hours heating and refer to the test specimens on which the water loss was continuously monitored.



																				Temperature Cycling				
TIME(HRS)	0	1	2	3	4	5	6	7	8	9	10	12	14	16	20	25	30	35	40	C	H	C	H	C
70°C	0	3,0	5,4	7,8	9,6	11,2	12,8	14,1	15,8	16,8	17,8	19,5	21,6	17,9	25,5	27,6	30,5	32,4	33,8	34,5	36,2	36,5	37,6	38,1
100°C	0	3,6	9,8	17,1	22,8	26,8	30,4	33,1	35,1	37,2	39,0	41,8	44,5	46,5	50,4	54,0	56,5	58,2	59,5	61,1	63,3	63,3	64,1	63,6
150°C	0	3,0	9,3	20,7	33,8	45,4	53,2	58,2	61,9	64,1	65,6	66,3	67,6	68,0	69,1	70,0	70,1	70,1	70,3	71,1	72,0	71,1	71,9	72,0

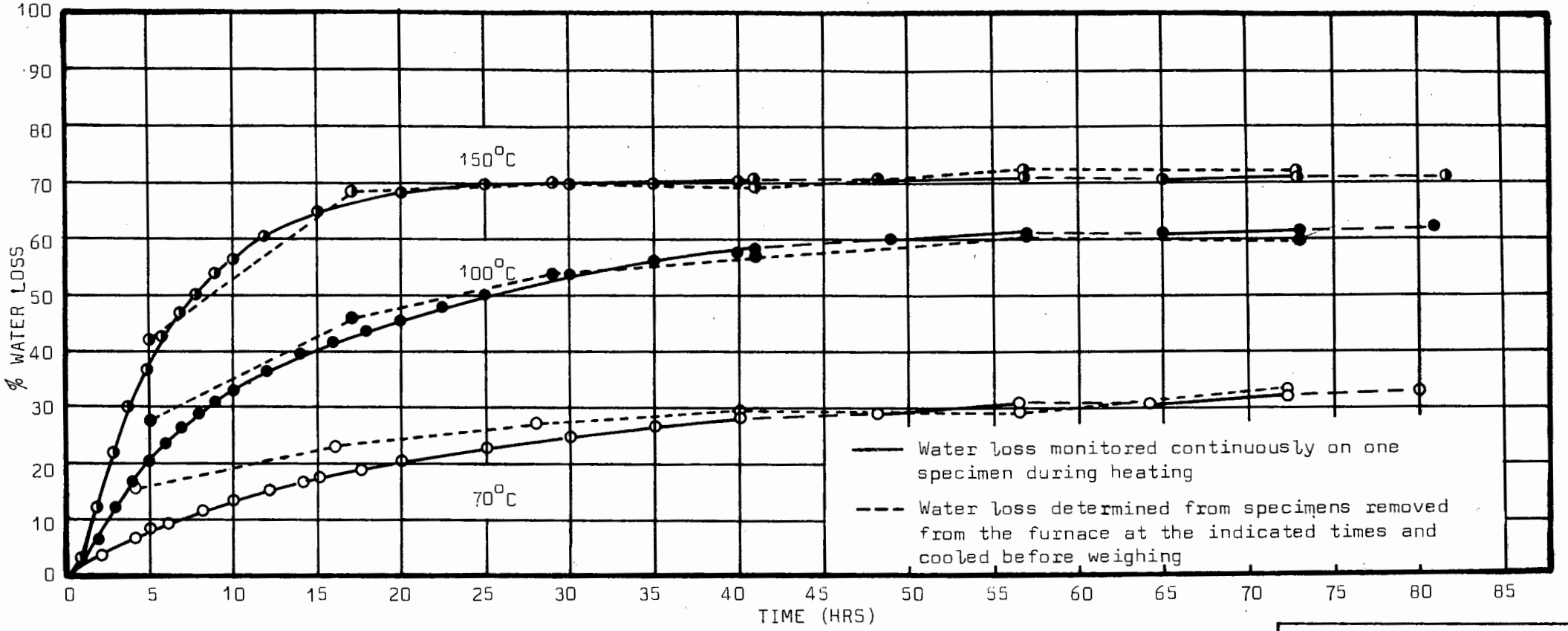
Values for water loss monitored continuously on one specimen during heating.

FIG.III.57: The water loss of test specimens heated to 70°C,100°C and 150°C respectively : Mix BCY.



	Values for water loss monitored continuously on one specimen during heating																		Temperature Cycling				
TIME(HRS)	1	2	3	4	5	6	7	8	9	10	12	20	25	30	35	40	45	46	C	H	C	H	C
250°C	4,0	16,5	39,3	63,4	72,0	74,1	75,4	75,9	76,0	76,0	76,2	77,0	77,2	77,6	77,7	77,7	77,7		78,1	78,8	78,2	78,7	78,7
400°C	3,0	13,8	36,5	62,2	73,3	77,2	79,9	81,9	83,2	84,0		84,9	85,6	85,9	86,0	86,1	86,5		86,2	87,0	85,9	87,3	85,8

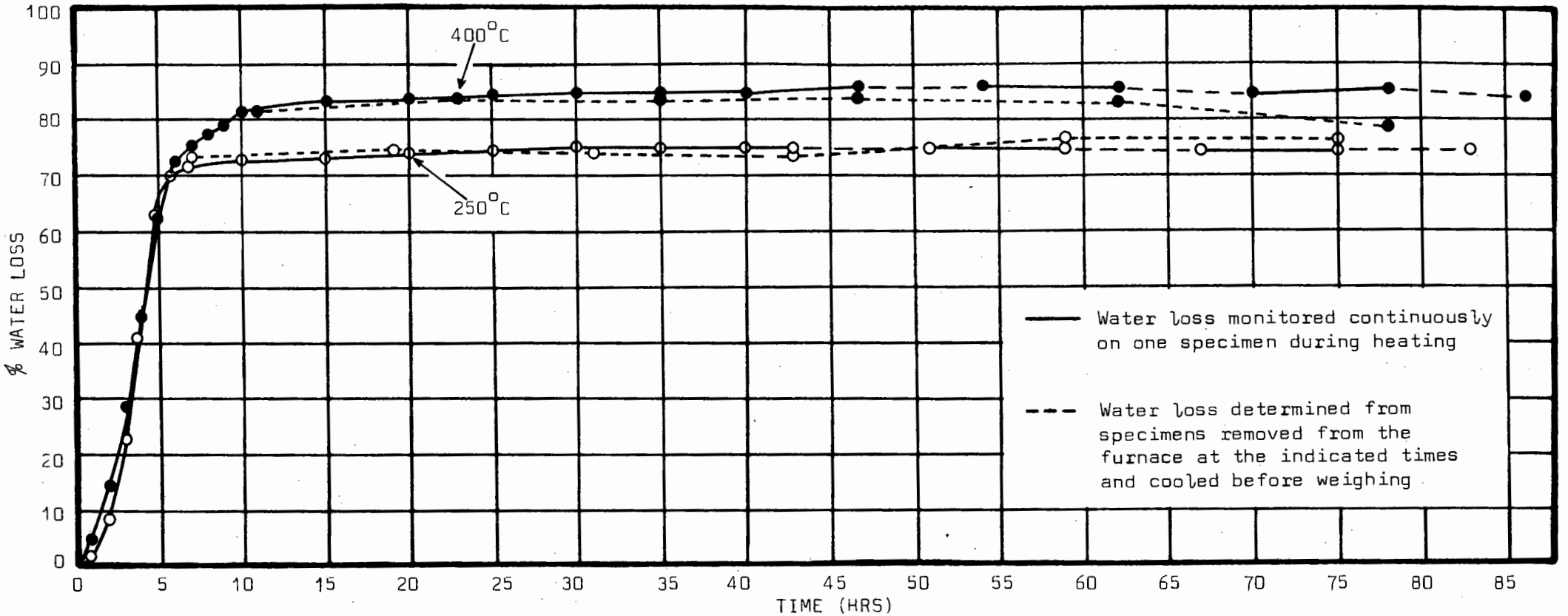
FIG.III.58: The water loss of test specimens heated to 250°C and 400°C respectively : Mix BCY.



Values for water loss monitored continuously on one specimen during heating.

TIME(HRS)	0	1	2	3	4	5	6	7	8	9	10	12	14	16	20	25	30	35	40	41	Temperature Cycling C	H	C	H	C
70°C	0	2,0	3,3	5,1	6,6	8,4	9,5	10,4	11,5	12,2	13,5	14,9	16,4	17,8	20,1	21,5	24,6	26,1	28,1		23,9	30,5	30,5	32,3	33,1
100°C	0	1,4	6,2	12,0	16,5	20,3	23,6	26,3	28,8	30,8	32,8	36,2	39,0	41,2	45,4	50,0	53,3	55,9	57,9	58,2	59,1	61,0	61,0	62,9	62,2
150°C	0	3,7	12,3	22,3	30,2	37,0	42,4	46,9	50,6	53,7	56,5	60,3	63,5	65,9	68,1	69,4	69,9	70,1	70,3	70,3	70,6	70,9	70,7	71,1	71,1

FIG.III.59: The water loss of test specimens heated to 70°C, 100°C and 150°C respectively : Mix BMY.



	Values for water loss monitored continuously on one specimen during heating																	Temperature Cycling				
TIME(HRS)	1	2	3	4	5	6	7	8	9	10	20	25	30	35	40	43	46	C	H	C	H	C
250°C	1,7	8,5	22,3	40,3	63,1	69,9	71,2			72,3	73,5	74,1	74,4	74,5	74,5	75,6		74,7	74,8	74,3	74,1	74,6
400°C	3,8	14,1	28,1	44,2	61,9	72,2	75,0	76,8	78,9	81,2	83,2	83,7	84,2	84,4	84,4		84,6	84,6	84,3	84,4	85,4	84,8

FIG.III.60: The water loss of test specimens heated to 250°C and 400°C respectively : Mix BMY.

TABLE III.6

The percentage water loss after 40 hours heating of test specimens made from the various concrete and mortar mixes

	MIX NAME	TEST TEMPERATURE				
		70°C	100°C	150°C	250°C	400°C
CONCRETE MIXES	BCY	33,8	59,5	70,3	77,7	86,1
	CCX	36,9	61,2	71,9	72,7	78,0
	CCY	30,0	65,2	72,8	75,8	79,7
MORTAR MIXES	BMY	28,1	57,9	70,3	74,5	84,4
	CMX	34,4	57,1	70,3	72,8	81,0
	CMY	31,5	61,2	69,4	72,9	82,3

(ii) At test temperatures of 70°C and 100°C both concrete and mortar test specimens exhibit water loss throughout the heating period. Further water loss occurs during the period when test specimens are subjected to temperature cycling. At 100°C the percentage water loss is always greater than the percentage of capillary water in the concrete or mortar specimens. Consequently, it appears that all the capillary water (free water) is removed at this temperature level, and also a certain proportion of either the gel pore water or the chemically combined water.

(iii) Test specimens heated to 150°C attain approximately constant mass after a heating period of 20 hours. However, the values tabulated in Figure A.III.1 to Figure A.III.12 in APPENDIX III indicate that a small, but nevertheless significant, further water loss does occur during the remainder of the heating period at 150°C. It is particularly interesting to compare the values of water loss after 40 hours heating to the total amount of capillary pore water and gel pore water in the various concrete mixes. This is shown in Table III.7, the water loss values referring to the test specimens on which the water loss was continuously monitored.

TABLE III.7

A comparison between the percentage water loss of test specimens heated to 150°C and the total percentage water in the gel pores and capillary pores of test specimens

	Mix Name	W_c %	W_g %	W_c+W_g %	Water Loss after 40 hours at 150°C %
CONCRETE MIXES	BCY	44,1	25,3	69,4	70,3
	CCX	51,4	22,0	73,4	72,0
	CCY	51,5	21,9	73,4	72,8
MORTAR MIXES	BMY	44,3	25,2	69,5	70,3
	CMX	51,3	22,0	73,3	70,4
	CMY	51,3	22,1	73,4	69,4

From Table III.7 it is apparent that there is good agreement between the water loss of test specimens after 40 hours heating at 150°C and the total percentage water in the gel pores and capillary pores. It must be remembered, though, that at 150°C a certain amount of chemically combined water is probably included in the 40 hours water loss values. However, the data suggest that at 150°C most of the gel pore water and capillary water has been removed from the concrete and mortar test specimens.

(iv) At temperatures of 250°C and 400°C the test specimens attain approximately constant mass immediately that the desired temperature level is attained. However, a further small water loss occurs during the heating period when the temperature remained constant at these temperature levels. This is illustrated in Table III.8 which shows the percentage water loss of test specimens after 20 hours and after 40 hours heating at test temperatures of 250°C and 400°C.

TABLE III.8

The water loss of test specimens after 20 hours and 40 hours heating at test temperatures of 250°C and 400°C

	Mix Name	250°C		400°C	
		Water Loss after 20 hours %	Water Loss after 40 hours %	Water Loss after 20 hours %	Water Loss after 40 hours %
CONCRETE MIXES	BCY	77,0	77,7	84,9	86,1
	CCX	72,0	72,7	77,2	78,0
	CCY	74,9	75,8	78,7	79,7
MORTAR MIXES	BMY	73,5	74,5	83,2	84,4
	CMX	72,0	72,8	80,2	81,0
	CMY	72,0	72,9	81,4	82,3

It is apparent from Table III.8 that the water loss after 40 hours heating at temperatures of either 250°C or 400°C is always approximately 1% greater than the water loss after 20 hours heating at these temperature levels. Furthermore, it would appear that this water loss is largely due to the removal of chemically combined water since at 400°C, and usually at 250°C, the percentage water loss exceeds the total percentage of gel pore and capillary pore water.

The percentage water loss determined on test specimens which were removed from Furnace No. 2 at various times during the heating period, cooled and immersed in water for 7 days before weighing are given in APPENDIX II, Table A.II.1 to Table A.II.42. These values of water loss indicate that test specimens which were re-immersed in water for 1 week after cooling from the test temperature usually did not achieve full saturation, i.e. the water gained by the test specimen during the 1 week soaking period was approximately 3% to 5% less than the water loss which had occurred during heating. In preliminary tests it was found that soaking the test specimens for 2 weeks after cooling made no appreciable difference to the amount of water gained. Consequently, the 1 week soaking period was used. These data indicate a most peculiar trend as regards the effect of temperature level on the water gained during re-saturation. Table III.9 shows the percentage water loss of test specimens (made from the various concrete and mortar mixes) which were cooled from temperatures of either 70°C, 100°C, 150°C, 250°C or 400°C and soaked in water for 7 days before

weighing. Each water loss value shown in Table III.9 is the mean value for test specimens of a particular mix at a particular test temperature.

TABLE III.9

The mean water loss (%) of test specimens cooled from the indicated temperature levels and immersed in water for 7 days before weighing

	Mix Name	TEST TEMPERATURES				
		70°C	100°C	150°C	250°C	400°C
CONCRETE MIXES	BCY	3,5	4,6	5,1	3,6	2,1
	CCX	3,8	3,7	5,3	3,2	1,5
	CCY	2,8	5,5	6,3	5,4	1,3
MORTAR MIXES	BMY	5,0	5,2	6,5	6,2	2,5
	CMX	3,7	5,2	7,8	3,7	2,9
	CMY	5,1	4,2	5,7	6,0	1,8

It is apparent from Table III.9 that the percentage water loss of test specimens which were cooled from temperatures of either 70°C or 100°C and soaked in water for 7 days is lower than the percentage water loss of test specimens which were cooled from 150°C and soaked in water for 7 days. This is to be expected since test specimens which were heated to 150°C underwent greater water loss during the heating period than specimens heated to either 70°C or 100°C. However, Table III.9 indicates that the test specimens which were soaked in water for 7 days after cooling from either 250°C or 400°C had significantly lower water loss than test specimens which were soaked in water after cooling from 150°C. Furthermore, it is apparent that the test specimens cooled from 400°C and soaked in water for 7 days before weighing always had lower water loss than test specimens cooled from 250°C and soaked before weighing. It is possible that these results indicate the initiation of microcracking within the test specimens, i.e. above 150°C microcracks within the test specimens are filled with water during re-saturation. Consequently, the test specimens cooled from 250°C and 400°C exhibit lower water loss after re-saturation than test specimens which underwent drying at lower temperature levels.

CHAPTER 7 : THE RESIDUAL LINEAR DEFORMATION OF CONCRETE AND MORTAR TEST SPECIMENS AFTER COOLING FROM THE VARIOUS TEST TEMPERATURE LEVELS

The residual linear deformation was determined for test specimens either:

(i) after cooling from the various temperature levels, or

(ii) after cooling from the various temperature levels and 7 days soaking in water.

The results of these measurements are given in APPENDIX II, Table A.II.1 to Table A.II.42. The data for test specimens which were removed from Furnace No. 2 (Waterbath No. 2) at various times during the heating period * are shown graphically in Figure III.61 to Figure III.66. Figure III.61 illustrates the maximum and minimum residual linear deformation which occurred during the heating period for specimens made from the concrete mix BCY and tested as in (i) and (ii) above. Figure III.62 and Figure III.63 shows the data for the concrete mixes CCX and CCY respectively, and Figure III.64, Figure III.65 and Figure III.66 the data for the mortar mixes BMY, CMX and CMY respectively.

7.1 The Residual Linear Deformation of Test Specimens after Cooling from the Various Test Temperatures

7.1.1 Concrete test specimens

The data in Figure III.61, Figure III.62 and Figure III.63 indicate that for concrete test specimens which underwent drying during heating:

(i) The residual linear deformation of test specimens cooled from 70°C is always a contraction of the test specimen. The extent of the contraction varied for the three different concrete mixes but was usually between 0,13 mm/m and 0,23 mm/m.

(ii) Concrete test specimens cooled from 100°C always exhibit greater contraction than test specimens cooled from 70°C. The values of the residual contraction ranged between 0,13 mm/m and 0,28 mm/m.

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* This refers to the heating period prior to the period of temperature cycling.

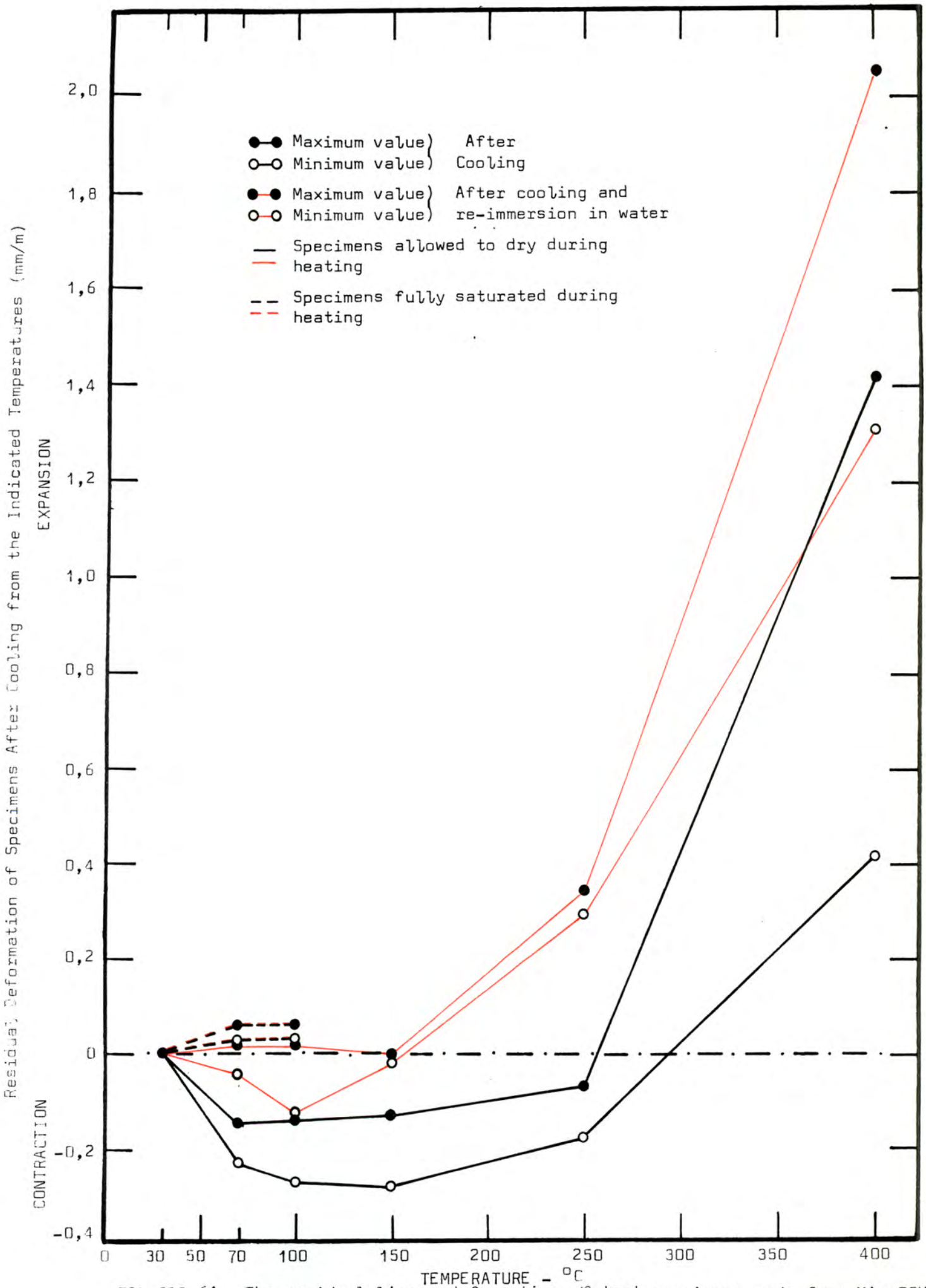

FIG. III.61: The residual linear deformation of test specimens made from Mix BCY.

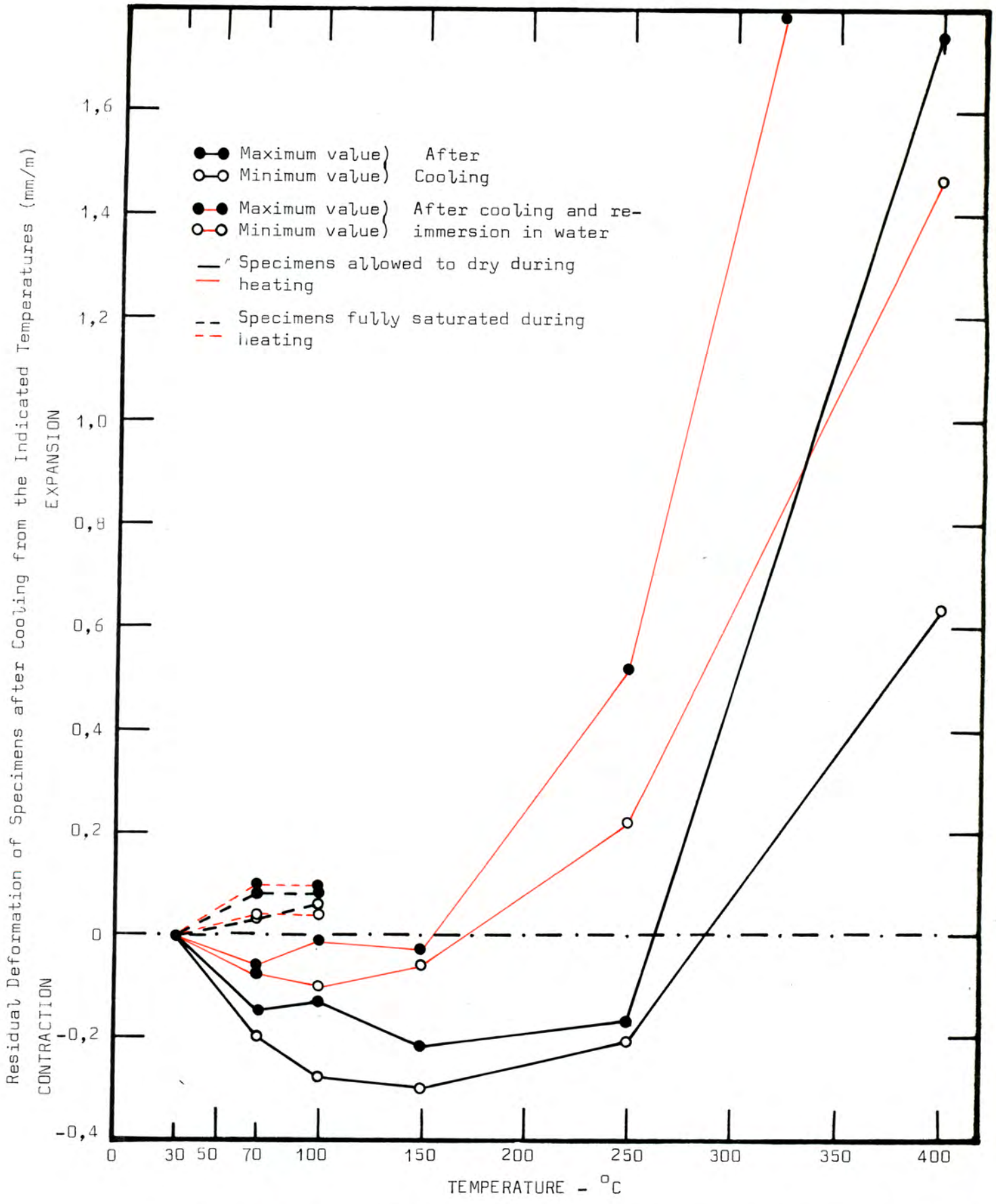

FIG.III.62: The residual linear deformation of test specimens made from Mix CCX.

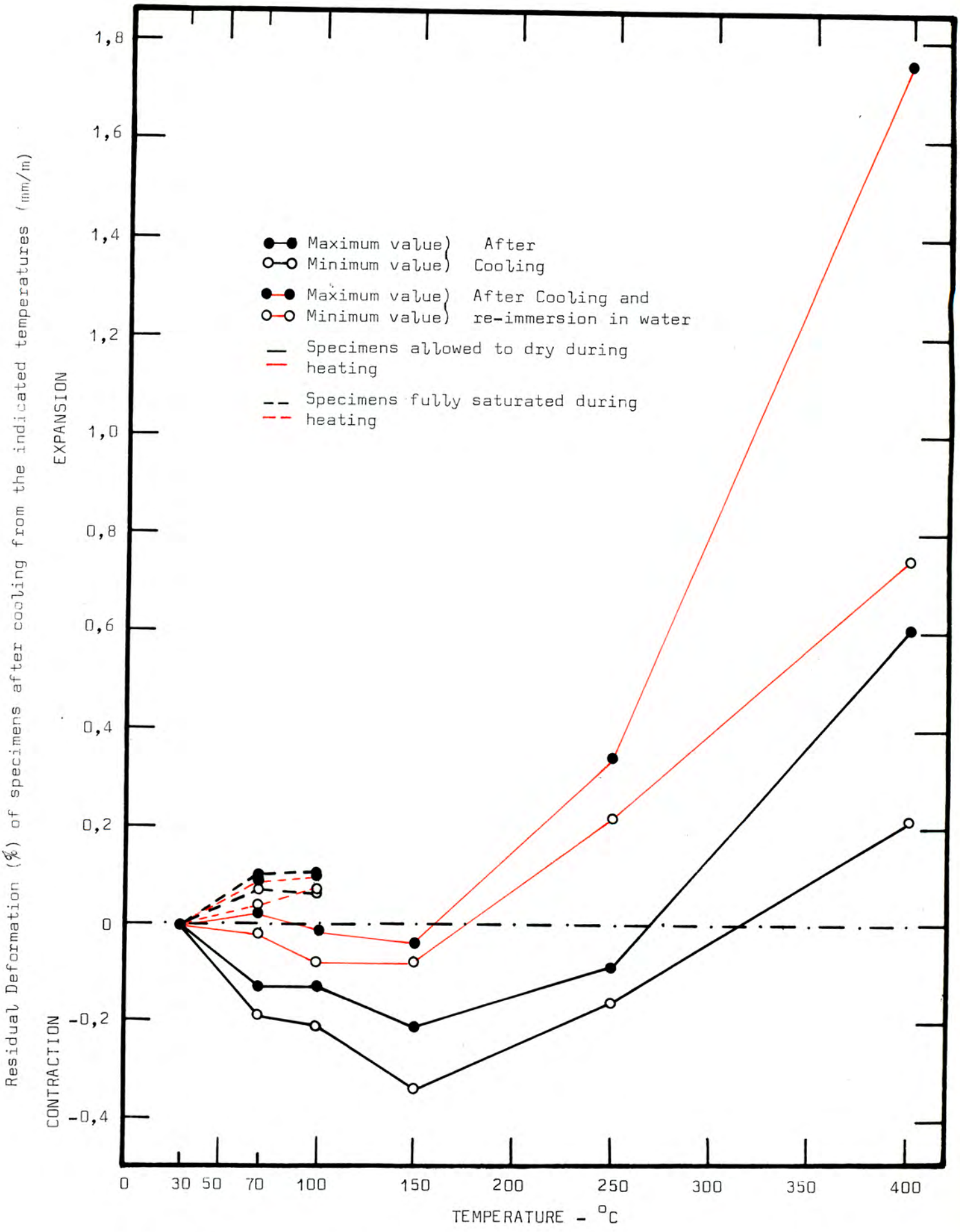

FIG.III.63: The residual linear deformation of test specimens made from Mix CCY.

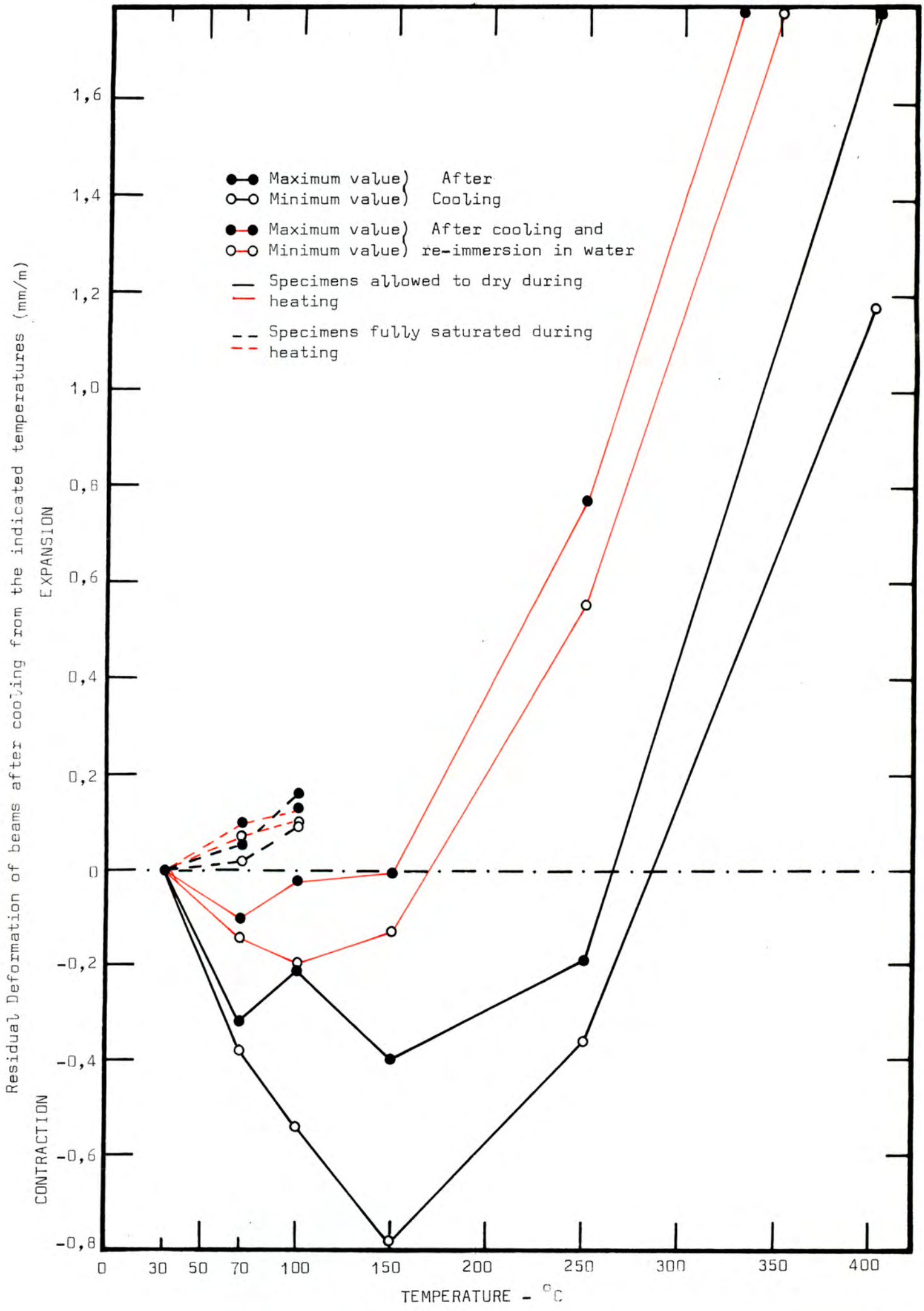

FIG.III.64: The residual linear deformation of test specimens made from Mix BMY.

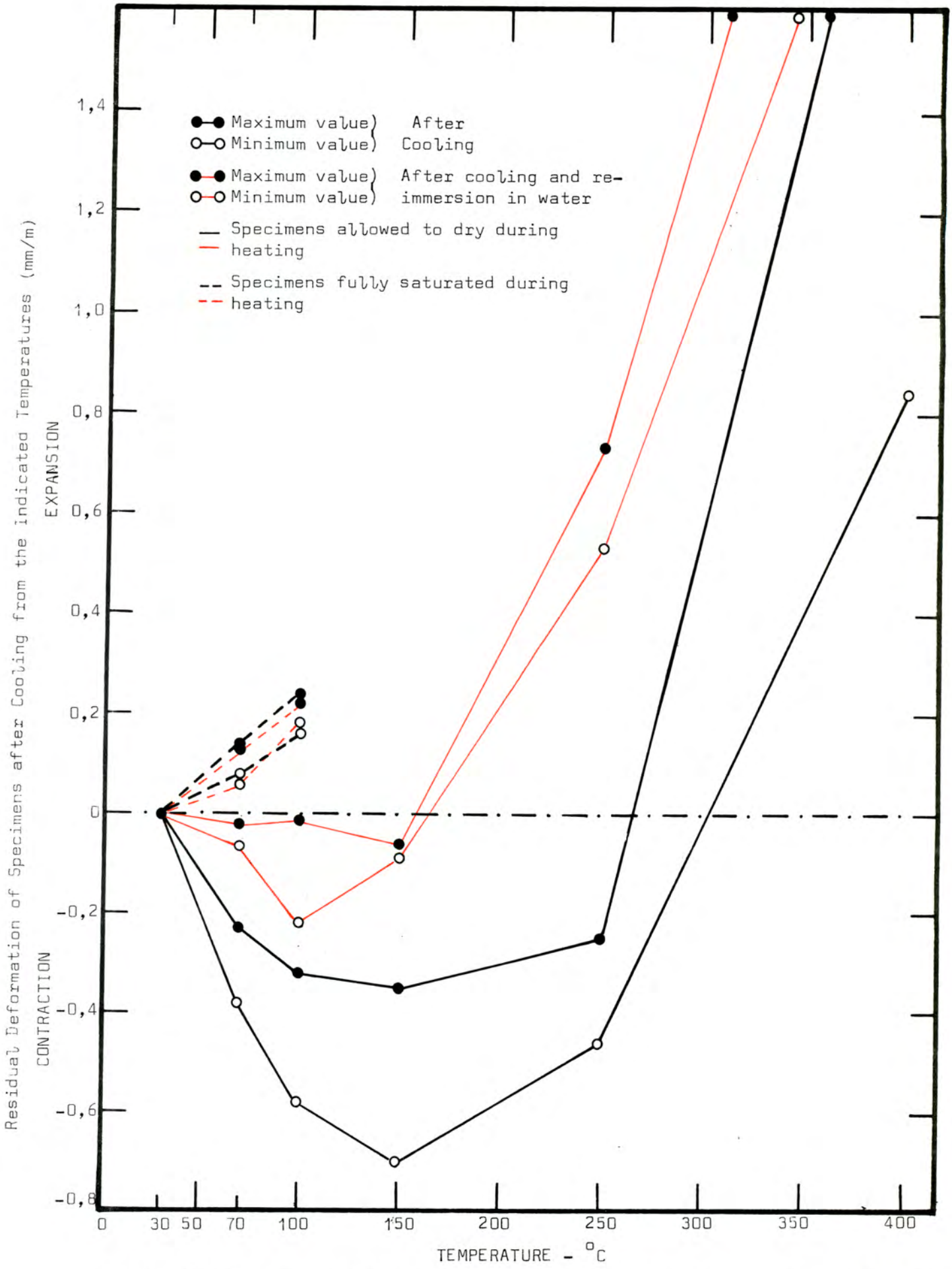

FIG.III.65: The residual linear deformation of test specimens made from Mix CMX.

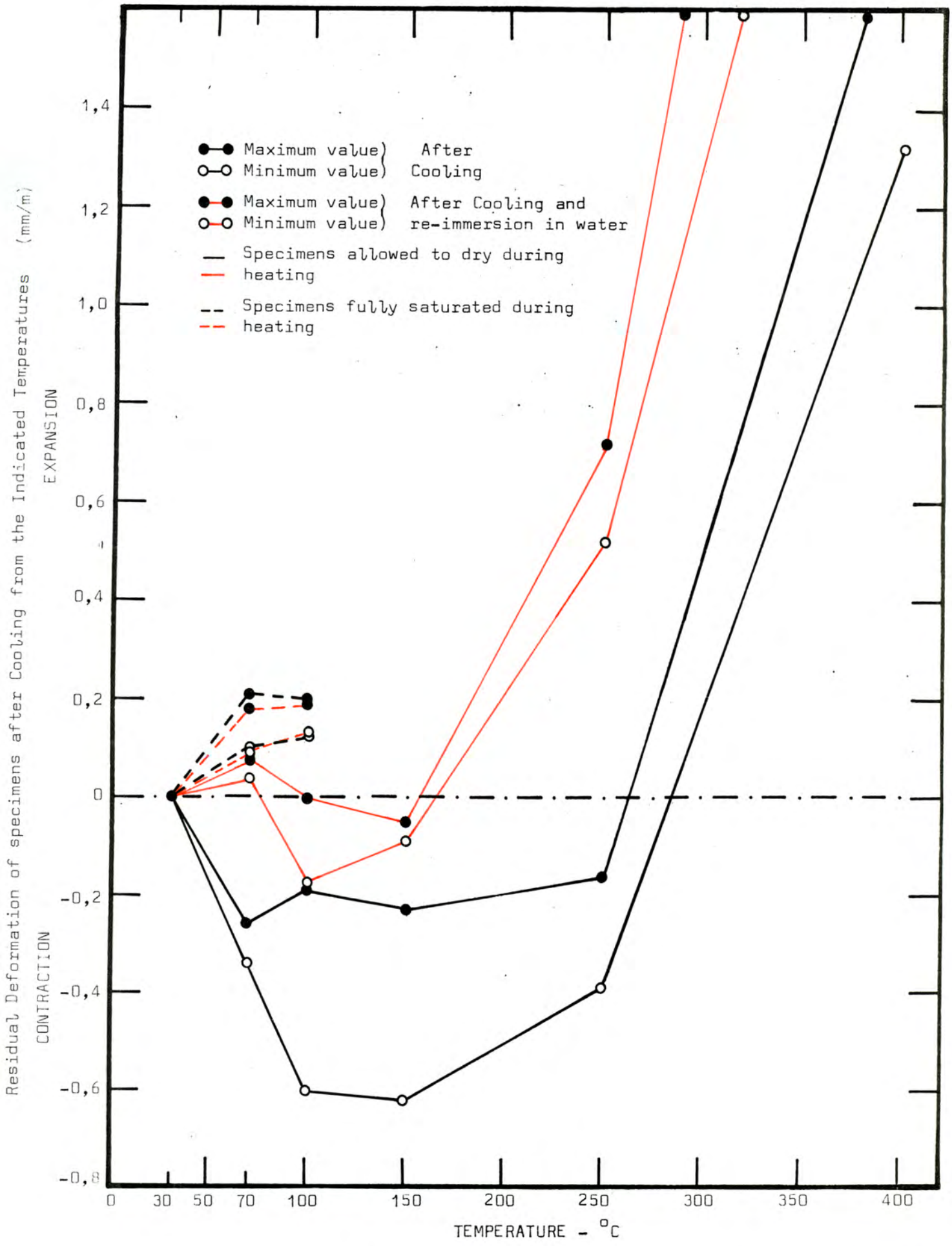

FIG.III.66: The residual linear deformation of test specimens made from Mix CMY.

(iii) The greatest contraction of concrete test specimens occurred for specimens cooled from 150°C. These values of residual contraction were always larger than the residual contraction at 100°C, and were between 0,13 mm/m and 0,34 mm/m.

(iv) Test specimens cooled from 250°C always exhibit residual contraction. However, the residual contraction is not as large as that exhibited by test specimens cooled from either 70°C, 100°C or 150°C. The values of residual contraction for specimens cooled from 250°C range from 0,07 mm/m to 0,21 mm/m.

(v) Concrete test specimens always have a residual expansion when cooled from 400°C. Values of the residual expansion range between 0,21 mm/m to 1,74 mm/m, i.e. the magnitude of the residual expansion is sometimes as much as 6 times greater than the maximum residual contraction exhibited by test specimens cooled from 150°C.

Figure III.61, Figure III.62 and Figure III.63 show also the residual linear deformation of test specimens which remained fully saturated during heating. These results indicate that:

(i) Concrete test specimens cooled from 70°C always exhibit a residual expansion of between 0,03 mm/m and 0,10 mm/m.

(ii) The residual expansion of saturated test specimens cooled from 100°C is not markedly different from that of test specimens cooled from 70°C. Values of the residual expansion range between 0,03 mm/m and 0,11 mm/m.

7.1.2 Mortar Test Specimens

The residual linear deformation of mortar test specimens after cooling from the different temperature levels are shown in Figure III.64, Figure III.65 and Figure III.66 for mixes BMY, CMX and CMY respectively. The results for test specimens which underwent drying during heating indicate that the residual linear deformation of mortar test specimens follows almost exactly a pattern similar to the residual linear deformation of concrete test specimens. However, the magnitude of both residual contraction and residual expansion is always greater for mortar test specimens than for concrete test specimens, viz:

(i) At 70°C the residual contraction of the various mortar mixes ranged from 0,23 mm/m to 0,38 mm/m,

(ii) The residual contraction of mortar test specimens cooled from 100°C ranged between 0,19 mm/m and 0,60 mm/m,

(iii) Test specimens cooled from 150°C exhibited greater residual contraction than test specimens cooled from either 70°C or 100°C; the values of residual contraction ranged from 0,23 mm/m to 0,78 mm/m,

(iv) The residual contraction of test specimens cooled from 250°C was less than the residual contraction of test specimens cooled from either 100°C or 150°C, and approximately the same as the residual contraction of test specimens cooled from 70°C. The residual contraction of test specimens cooled from 250°C was between 0,16 mm/m and 0,47 mm/m,

(v) Mortar test specimens cooled from 400°C always exhibit a residual expansion. The residual expansion ranged between 80 mm/m and 233 mm/m.

The values of residual linear deformation for mortar test specimens which remained fully saturated during heating are illustrated in Figure III.64, Figure III.65 and Figure III.66 for the mortar mixes BMY, CMX and CMY respectively. Test specimens that were cooled from 70°C always exhibit a residual expansion. However, the magnitude of the residual expansion was different for the various mortar mixes, viz. mix BMY exhibited a residual expansion of between 0,02 mm/m and 0,05 mm/m, mix CMX a residual expansion of between 0,08 mm/m and 0,14 mm/m, and mix CMY a residual expansion ranging from 0,10 mm/m to 0,21 mm/m. These values are always greater than the values of residual expansion exhibited by the corresponding concrete test specimens cooled from 70°C.

Mortar test specimens cooled from 100°C also exhibit residual expansion. Values of the residual expansion for the various mortar mixes range between 0,09 mm/m and 0,24 mm/m, these values being approximately twice as great as the value of residual expansion for saturated concrete test specimens cooled from 100°C. Furthermore, it does appear that the residual expansion of mortar test specimens cooled from 100°C is significantly larger than the residual expansion of mortar test specimens cooled from 70°C. However, this cannot be stated with certainty since for mix CMY the two respective values of residual expansion are almost identical.

7.2 The Residual Linear Deformation of Test Specimens after Cooling and 7 Days Soaking in Water

The values of residual linear deformation measured on concrete test specimens which were cooled from the various temperature levels and immersed in water for 7 days before testing, are shown in Figure III.61, Figure III.62 and Figure III.63 for mixes BCY, CCX and CCY respectively. The data for specimens made from the mortar mixes BMY, CMX and CMY are illustrated in Figure III.64, Figure III.65 and Figure III.66 respectively. In each diagram the maximum and minimum residual value is illustrated. These maximum and minimum values refer only to test specimens which were removed from the furnace (waterbath) at various times during the heating period prior to temperature cycling.

7.2.1 Concrete test specimens

Figure III.61 to Figure III.63 indicate that for concrete test specimens which underwent drying during heating:

(i) The residual linear deformation of test specimens cooled from 70°C and immersed in water for 7 days ranges from a small residual expansion of 0,02 mm/m to a residual contraction of 0,08 mm/m. The residual contraction of the test specimen is not as great as the residual contraction which occurred for mortar specimens tested immediately after cooling from 70°C.

(ii) Test specimens cooled from 100°C and immersed in water for 7 days usually exhibit a residual contraction. Values of the residual contraction range between 0,01 mm/m and 0,12 mm/m and are usually greater than the values of residual contraction which occurred for test specimens immersed in water after cooling from 70°C.

(iii) Test specimens cooled from 150°C and immersed in water for 7 days before testing usually exhibit smaller residual contraction than test specimens which underwent similar treatment at a temperature of either 70°C or 100°C. Values of the residual contraction range between 0,0 and 0,08 mm/m. The result is particularly surprising since test specimens which were tested immediately after cooling from 150°C exhibit higher residual contraction than similar specimens cooled from either 70°C or 100°C.

(iv) The residual linear deformation of test specimens cooled from 250°C and soaked in water for 7 days is a residual expansion. The values

usually range between 0,22 mm/m and 0,52 mm/m. In this regard it should be noted that specimens which were tested immediately after cooling from 250°C always exhibited a residual contraction.

(v) Test specimens cooled from 400°C and immersed in water for 7 days before testing exhibit a residual expansion. The residual expansion was in some instances as high as 3,14 mm/m and was always greater than the residual expansion which occurred for specimens tested immediately after cooling from 400°C.

Concrete test specimens which remained fully saturated during heating and were cooled and stored in water for 7 days before testing, exhibit values of residual expansion which are almost identical to the values of residual expansions for concrete test specimens which were tested immediately after cooling. This applies to test temperatures of both 70°C and 100°C. Furthermore, it appears that the residual linear expansion of saturated concrete specimens cooled from 70°C and immersed in water for 7 days, are not significantly different from the residual expansions of specimens cooled from 100°C and immersed in water for 7 days before testing.

7.2.2 Mortar test specimens

The maximum and minimum residual linear deformation of mortar test specimens cooled from the various test temperatures and immersed in water for 7 days before testing, are shown in Figure III.64, Figure III.65 and Figure III.66 for mixes BMY, CMX and CMY respectively. The data for specimens that underwent drying during heating indicate that the residual linear deformation of mortar test specimens cooled from the various temperature levels follows exactly the same pattern as the residual linear deformation of concrete test specimens. However, the magnitude of the residual deformation is always greater for mortar test specimens than for concrete specimens. From Figure III.64 to Figure III.66 it is apparent that:

(i) Test specimens which were cooled from 70°C and immersed in water for 7 days before testing usually exhibit a residual contraction. The maximum residual contraction that occurred was 0,17 mm/m. However, in one instance (mix CMY) a residual expansion of 0,08 mm/m did occur.

(ii) the residual linear deformation of test specimens cooled from 100°C and immersed in water for 7 days before testing is always a residual contraction. The residual contraction ranges between 0,01 mm/m and 0,22 mm/m.

(iii) Mortar test specimens cooled from 150°C and immersed in water for 7 days always exhibit a residual contraction smaller than the residual contraction which occurred for test specimens cooled from 100°C. The values ranged between 0,0 and 0,15 mm/m.

(iv) For (i), (ii) and (iii) above, the respective values of residual contraction were always less than the values for residual contraction which occurred for mortar specimens tested immediately after cooling.

(v) Test specimens cooled from 250°C and immersed in water for 7 days before testing always exhibit a residual expansion. The residual expansion which occurred ranged between 0,52 mm/m and 0,77 mm/m. In this regard it should be remembered that mortar test specimens exhibit a residual contraction when tested immediately after cooling from 250°C.

(vi) Mortar test specimens cooled from 400°C and immersed in water for 7 days before testing always exhibit a residual expansion. The residual expansion is greater than that which occurred for specimens cooled from 250°C and also greater than the residual expansion exhibited by concrete specimens cooled from 400°C and immersed in water for 7 days before testing. The values for the residual expansion ranged between 2,42 mm/m and 3,40 mm/m.

Mortar test specimens which remained fully saturated during heating and were cooled and stored in water for 7 days before testing, have linear expansion values which are almost identical to the values of linear expansion measured on mortar test specimens immediately after cooling. This applies to test temperatures of both 70°C and 100°C. Mortar test specimens cooled from 70°C and soaked in water for 7 days have residual expansion which ranges between 0,06 mm/m and 0,18 mm/m. The values for test specimens cooled from 100°C and soaked in water for 7 days before testing range between 0,10 mm/m and 0,22 mm/m. It appears from these results that the mortar specimens cooled from 100°C and soaked in water for 7 days have values of residual expansion which are significantly larger than the values obtained on specimens cooled from 70°C and soaked in water before testing. Similar behaviour was not found for the concrete test specimens.

In the abovementioned results it is apparent that, for a particular mix at a particular test temperature, the maximum value of residual linear deformation for test specimens is usually appreciably different from the minimum value of residual linear deformation. These values were determined on test specimens which were removed from the furnace (waterbath) at various times during the heating period prior to temperature cycling. Consequently, it appears likely that the heating time had an influence on the values of residual linear deformation of test specimens; particularly for test specimens which underwent drying during heating since shrinkage is caused by water loss from the test specimens. In this regard, it was found in CHAPTER 6 that at all temperature levels the water loss * increased with time during the heating period. The effect of heating time is also indirectly illustrated by the values of residual deformation for test specimens which were subjected to temperature cycling. These data are shown in Figure III.67, Figure III.68 and Figure III.69 for the concrete mixes BCY, CCX and CCY respectively, and in Figure III.70, Figure III.71 and Figure III.72 for the mortar mixes BMY, CMX and CMY respectively. It is apparent that, in general, these results indicate exactly similar trends as the residual linear deformation results for test specimens which were not subjected to temperature cycling. However, for test specimens cooled from temperatures of either 70°C, 100°C, 150°C or 250°C, the difference between the maximum and minimum value of residual linear deformation for specimens subjected to temperature cycling is much smaller than the difference between the maximum and minimum residual linear deformation which occurred for test specimens not subjected to temperature cycling. It appears, therefore, that at these temperature levels the residual linear deformation of test specimens changes during the heating period prior to temperature cycling, and that little further change in the residual deformation occurs during temperature cycling. The effect of heating time and temperature cycling on the residual deformation of test specimens heated to 400°C is obscure, since specimens which were tested at various times during the heating period prior to temperature cycling, as well as test specimens which were subjected to temperature cycling, exhibit extraordinarily large differences between the maximum and minimum values of residual expansion. The effect of heating time and temperature cycling on the residual linear deformation is statistically determined in PART IV : STATISTICAL ANALYSIS.

Of particular interest in the residual linear deformation results is the behaviour of test specimens made from the various mortar mixes as compared to the behaviour

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* It should be remembered that loss of chemically combined water also results in shrinkage of test specimens. This was discussed in PART I.

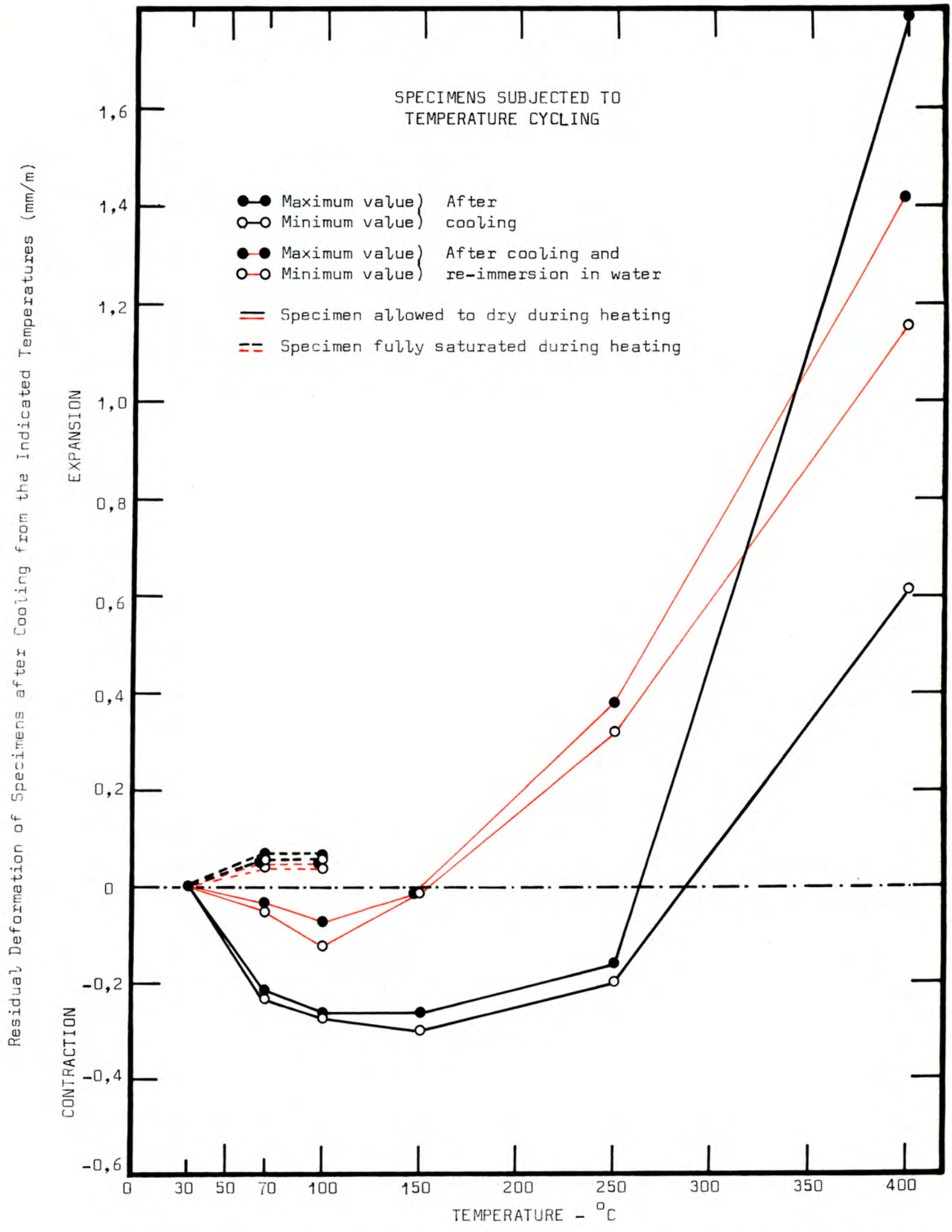

FIG.III.67: The residual linear deformation of test specimens made from Mix BCY.

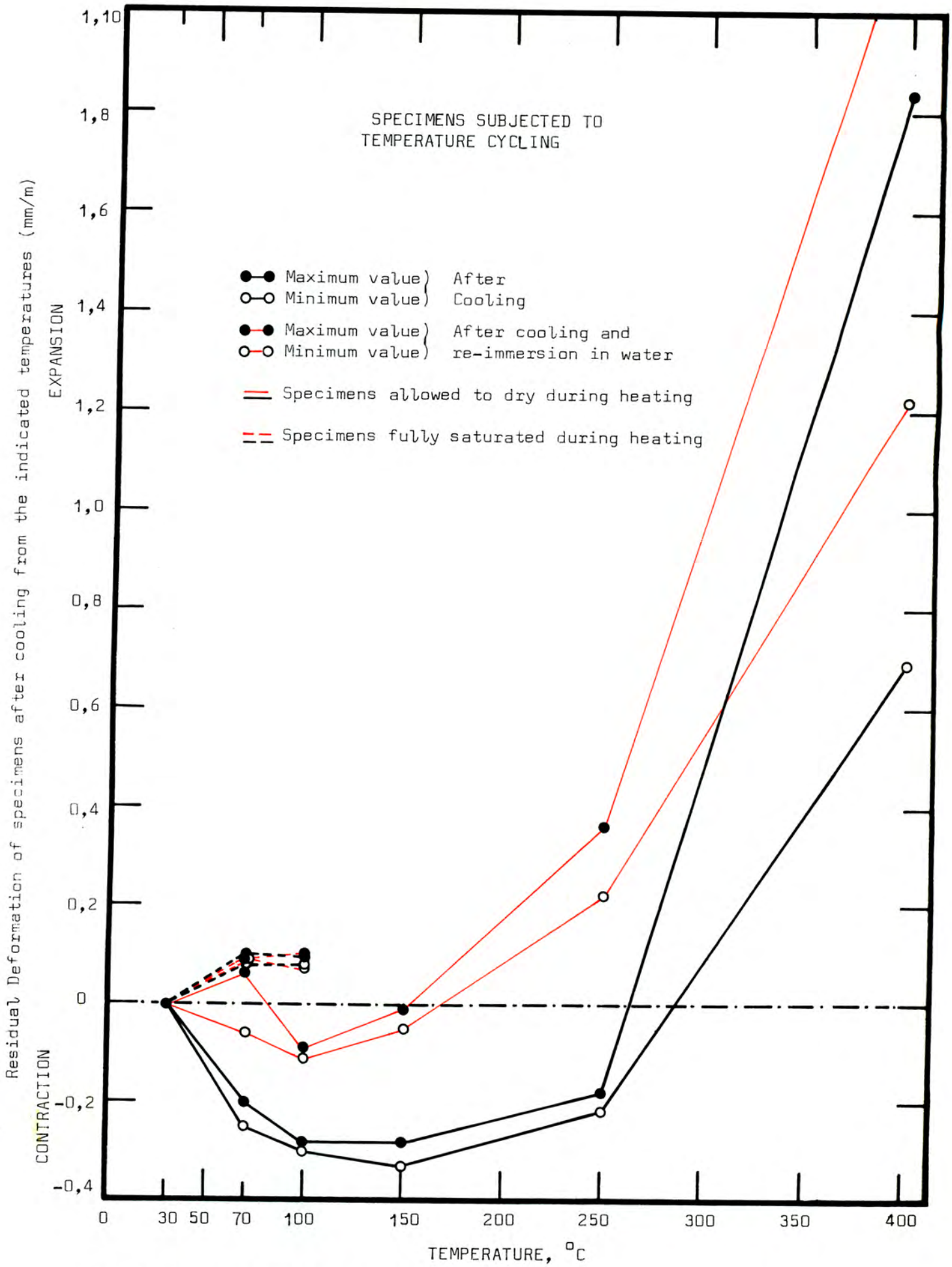

FIG.III.68: The residual linear deformation of test specimens made from Mix CCX.

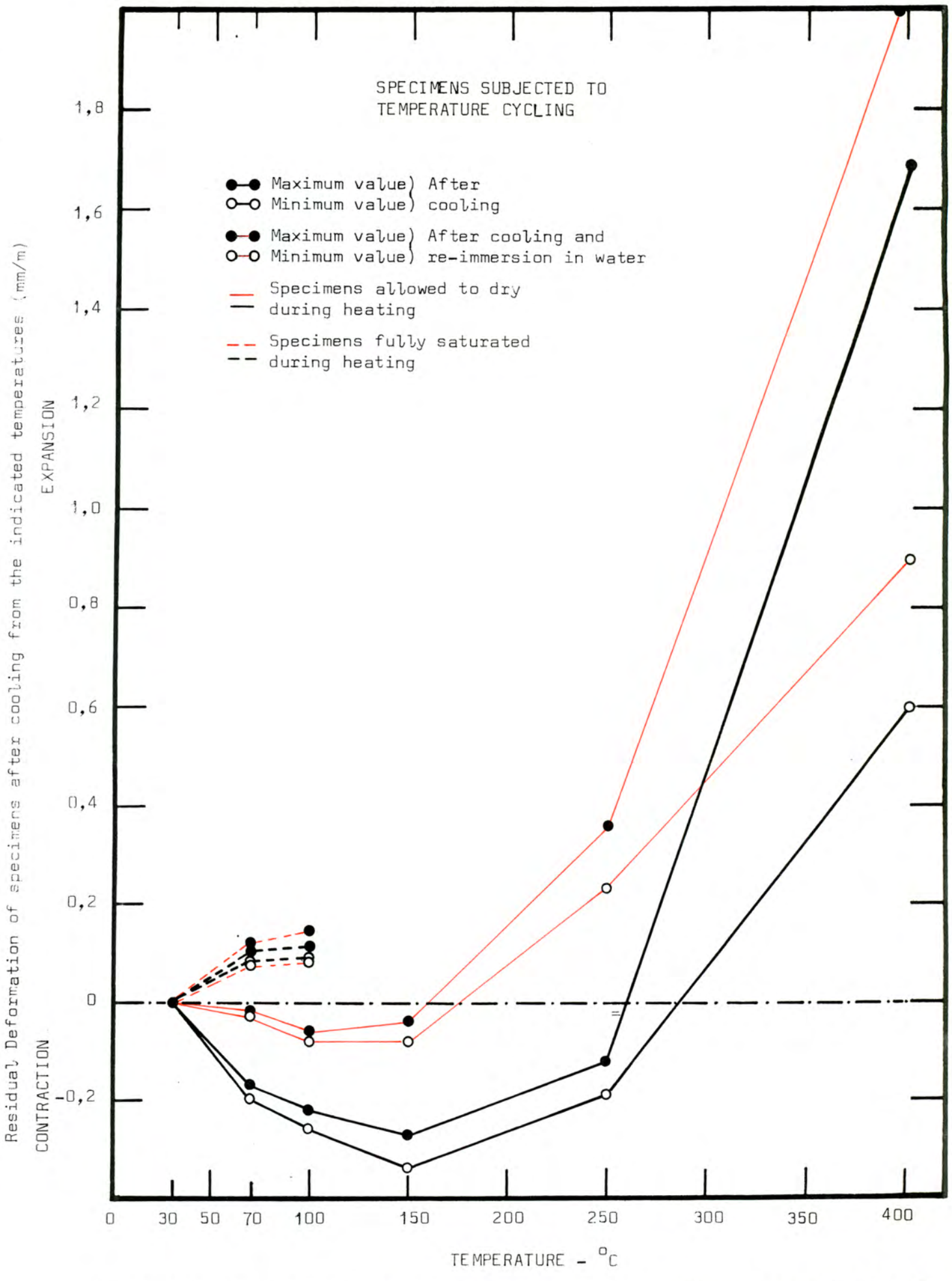

FIG.III.69: The residual linear deformation of test specimens made from Mix CCY.

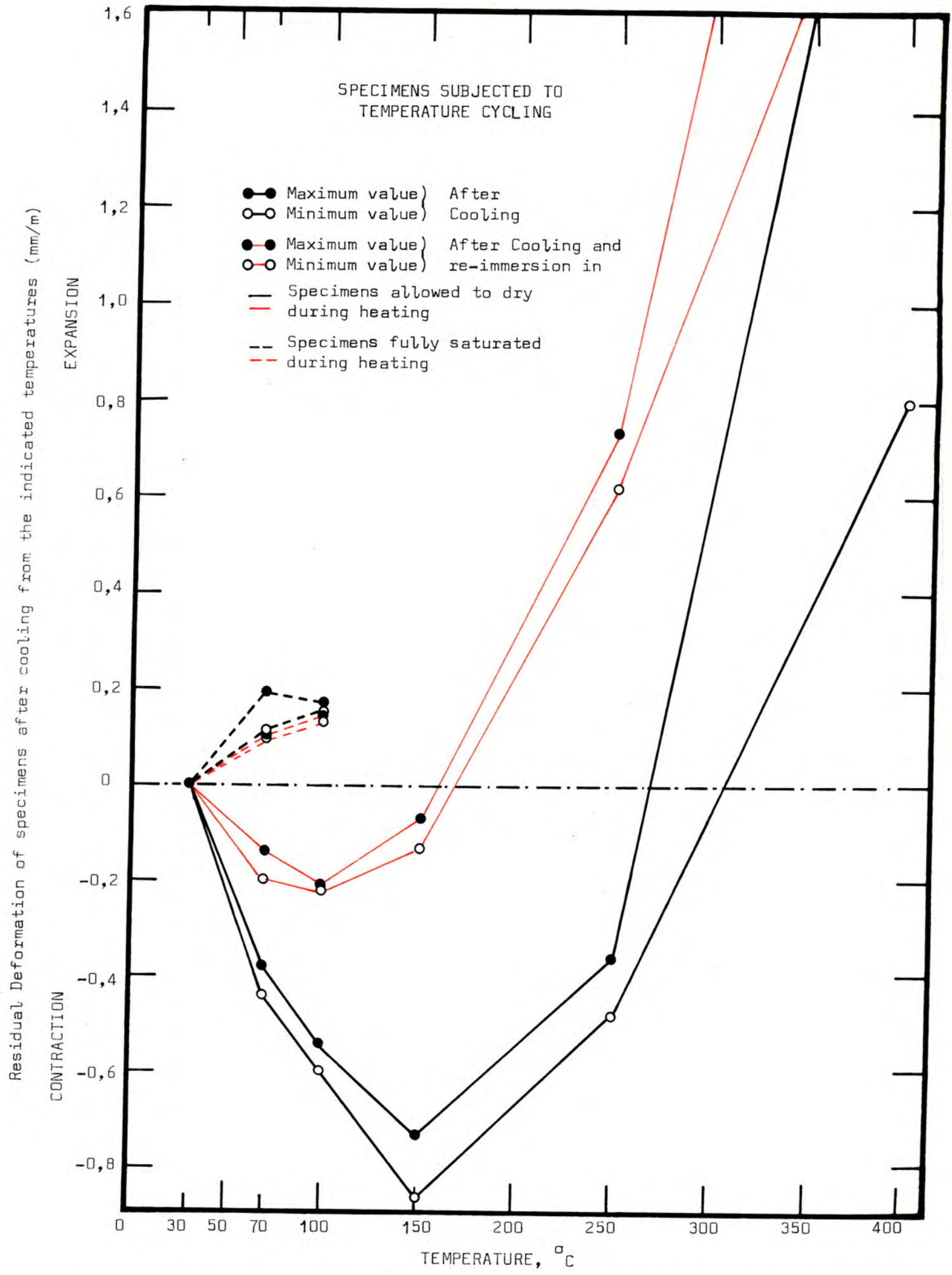

FIG.III.70. The residual linear deformation of test specimens made from Mix BMY.

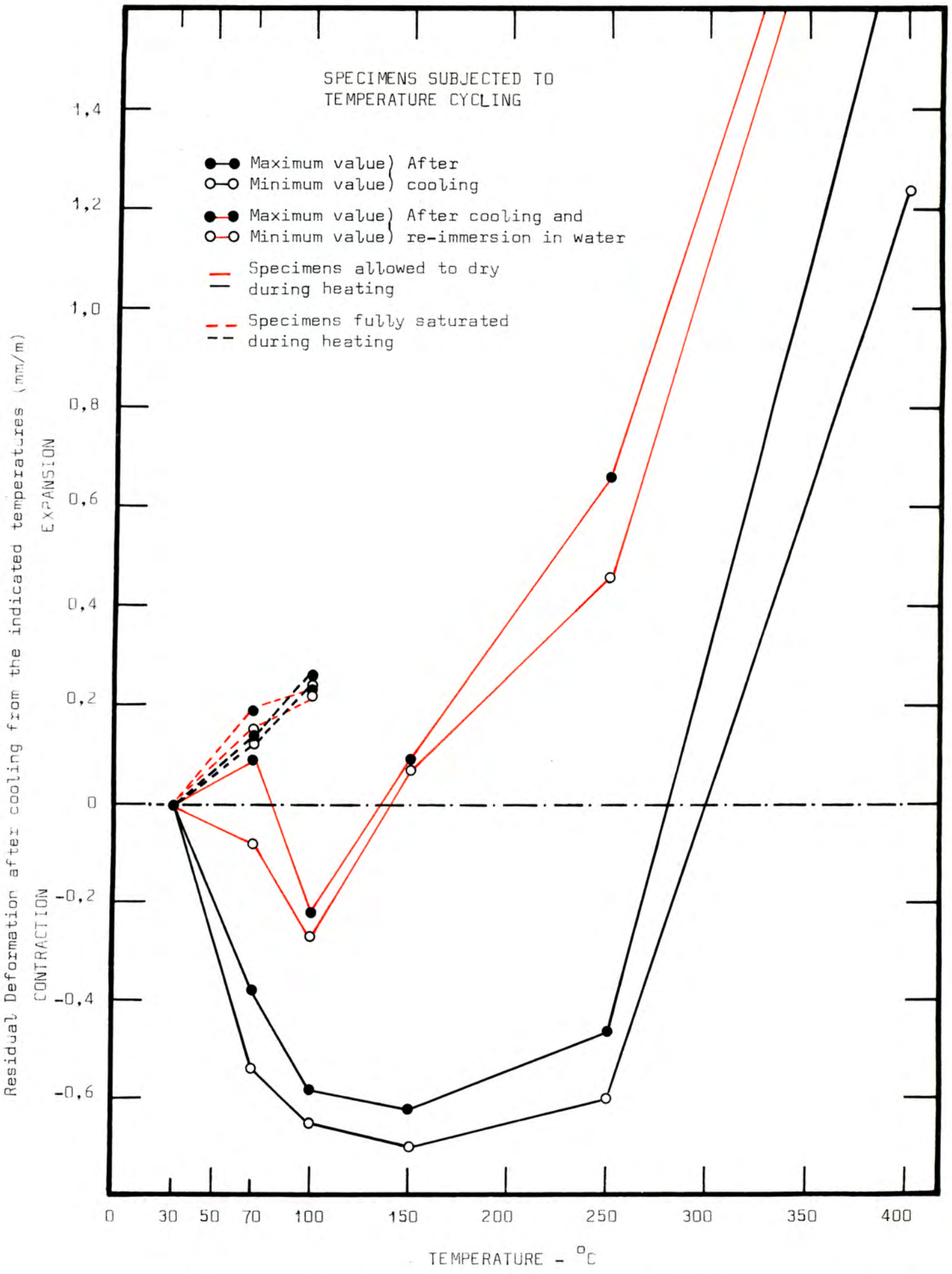

FIG.III.71: The residual linear deformation of test specimens made from Mix CMX.

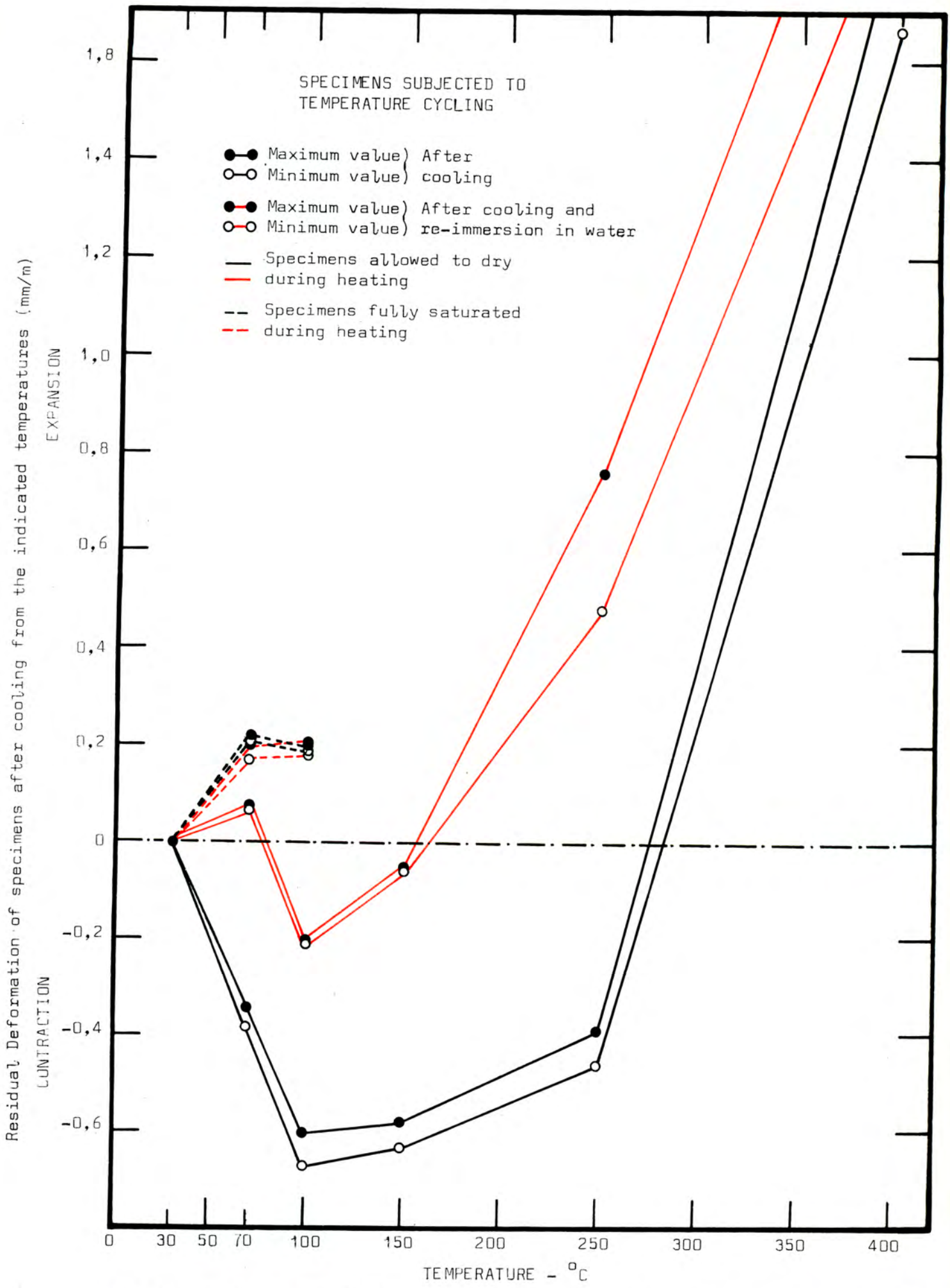

FIG.III./2: The residual linear deformation of test specimens made from Mix CMY.

of test specimens made from the various concrete mixes. In cases where the residual linear deformation was a contraction, the mortar test specimens always exhibit a contraction approximately twice as great as that exhibited by the corresponding concrete specimens. However, for specimens which were cooled from 250°C and soaked in water for 7 days the residual expansion of the mortar specimens is approximately twice as great as the residual expansion of the corresponding concrete test specimens. Consequently, it appears that the behaviour of the residual linear deformation of the concrete mixes is almost entirely dominated by the behaviour of the mortar which was used in manufacturing these concrete mixes.

CHAPTER 8 : THE LINEAR DEFORMATION OF CONCRETE AND MORTAR TEST SPECIMENS DURING HEATING

The results of the linear deformation measurements on heated concrete and mortar test specimens are illustrated graphically in APPENDIX IV, Figure A.IV.1 to Figure A.IV.42. Some typical linear deformation curves for the mortar mix CMY are shown in Figure III.73 to Figure III.79. Figure III.73 and Figure III.74 illustrate the linear deformation for mortar specimens of mix CMY heated to temperatures of 70°C and 100°C respectively, the test specimens having remained fully saturated for the duration of the heating period and during the temperature cycling period. Figure III.75, Figure III.76, Figure III.77, Figure III.78 and Figure III.79 show the linear deformation for mortar test specimens of mix CMY which underwent drying at temperatures of 70°C, 100°C, 150°C, 250°C and 400°C respectively.

The values for linear deformation reported above are the mean values of two independent determinations. These tests were performed on specimens which were exactly similar in all respects except that the age of the two test specimens differed by three days, i.e. the linear deformation was measured on two independent test specimens which had been cured for 28 days and 31 days respectively. In extensive preliminary tests it was found that the additional 3 days curing had not significant effect on the linear deformation of heated concrete and mortar specimens. Only the mean of the two determinations is reported. The mean value of linear deformation during heating was calculated after the two linear deformation curves had been corrected to take into account;

(i) the small fluctuations of the test specimen average temperature about the desired test temperature level,

(ii) the small, but nevertheless significant, expansion of the silica rods which coupled the test specimen to the linear deformation measuring apparatus.

The method of calculating these corrections to the linear deformation curves is given in APPENDIX I.5.

In all the diagrams showing linear deformation of heated specimens, viz. Figure III.73 to Figure III.79, and Figure A.IV.1 to Figure A.IV.42 in APPENDIX IV, the values which are indicated on the curves refer to either;

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* Standard humidity curing at 21°C and 100% relative humidity.

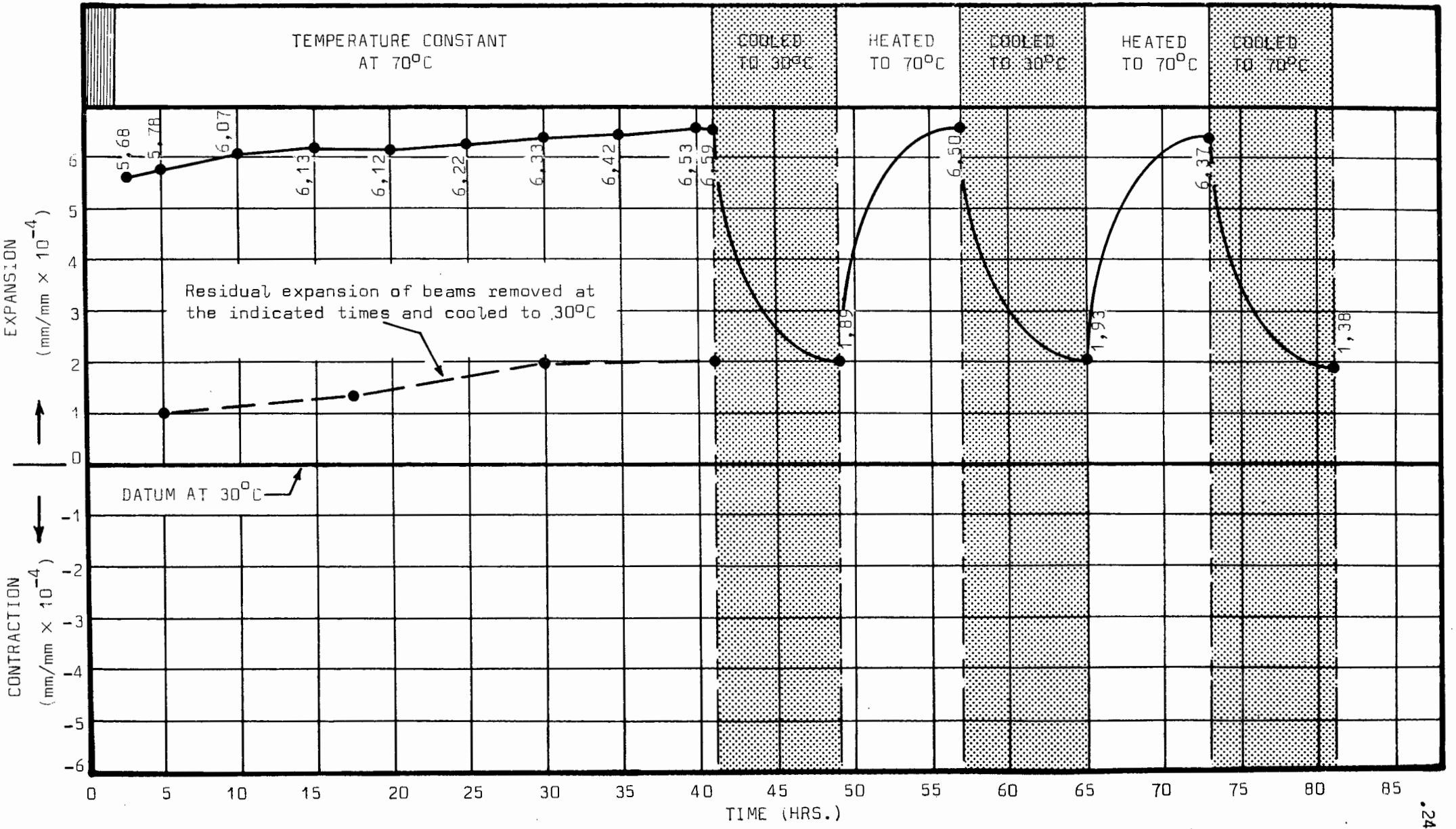

FIG.III.73: The linear deformation of test specimens which remained fully saturated at 70°C : Mix CMY.

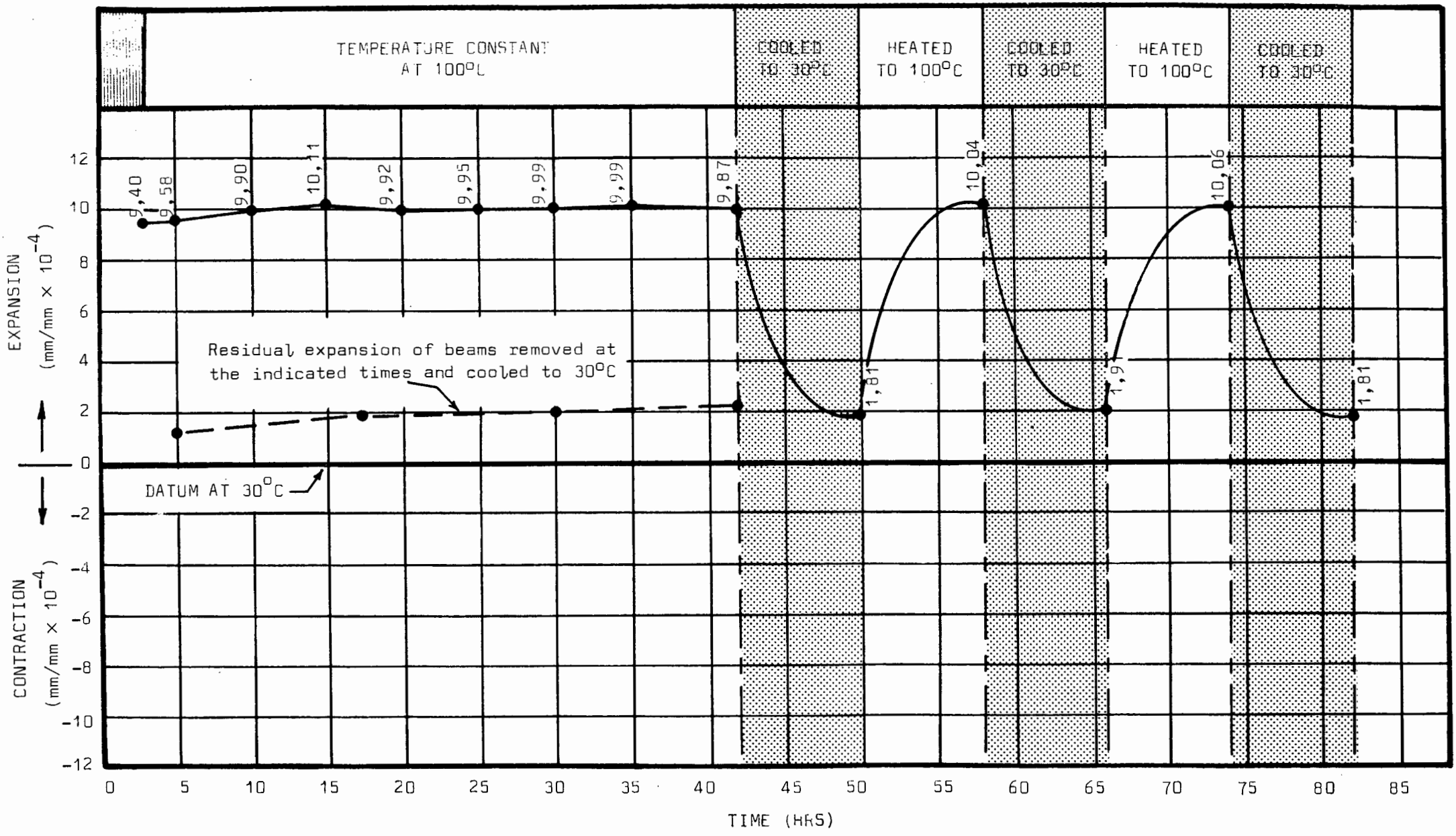

FIG.III.74: The linear deformation of test specimens which remained fully saturated at 100°C : Mix CMY.

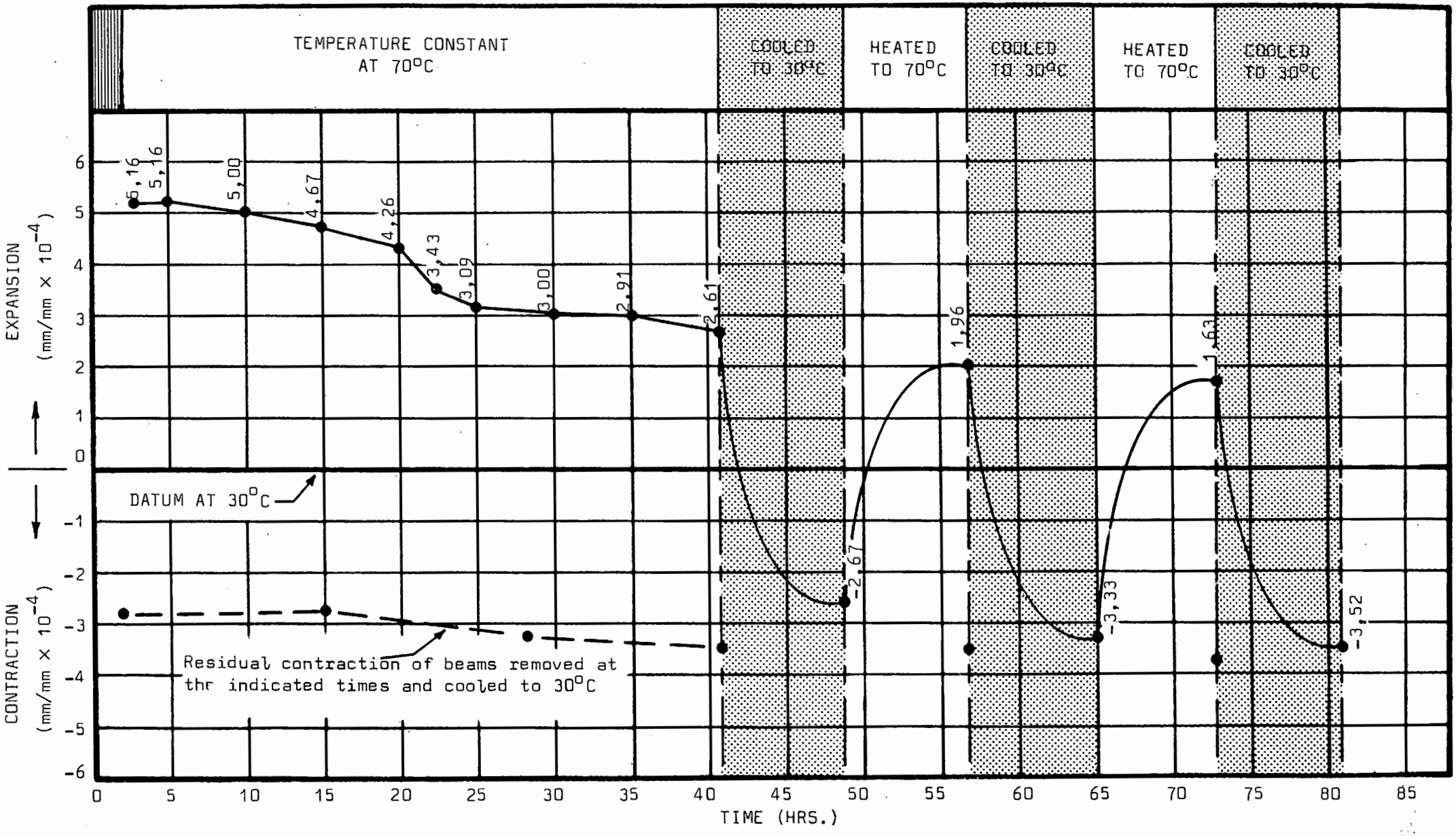

FIG.III.75: The linear deformation of test specimens which underwent drying at 70°C: Mix CMY.

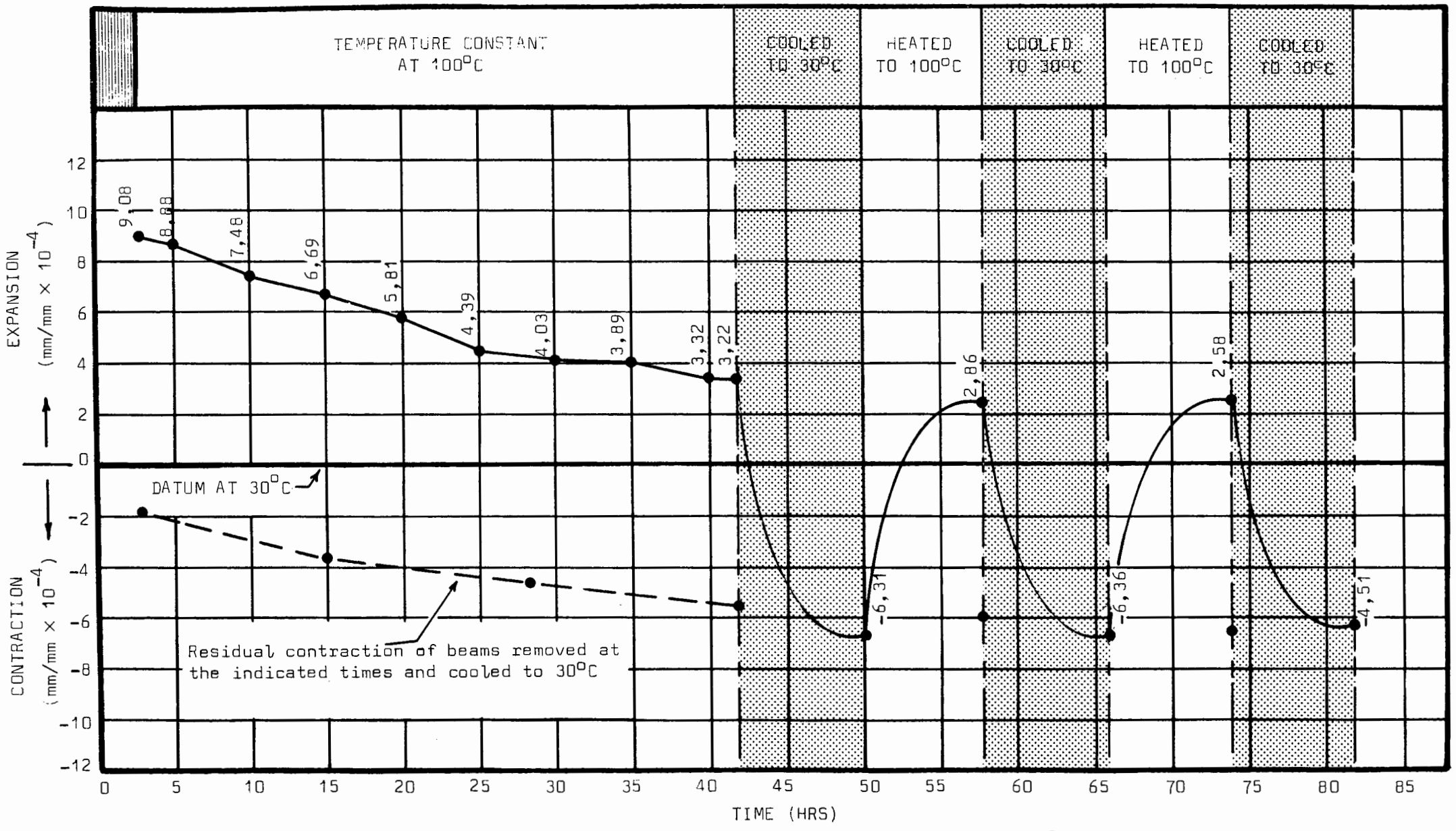

FIG.III.76: The linear deformation of test specimens which underwent drying at 100°C : Mix CMY.

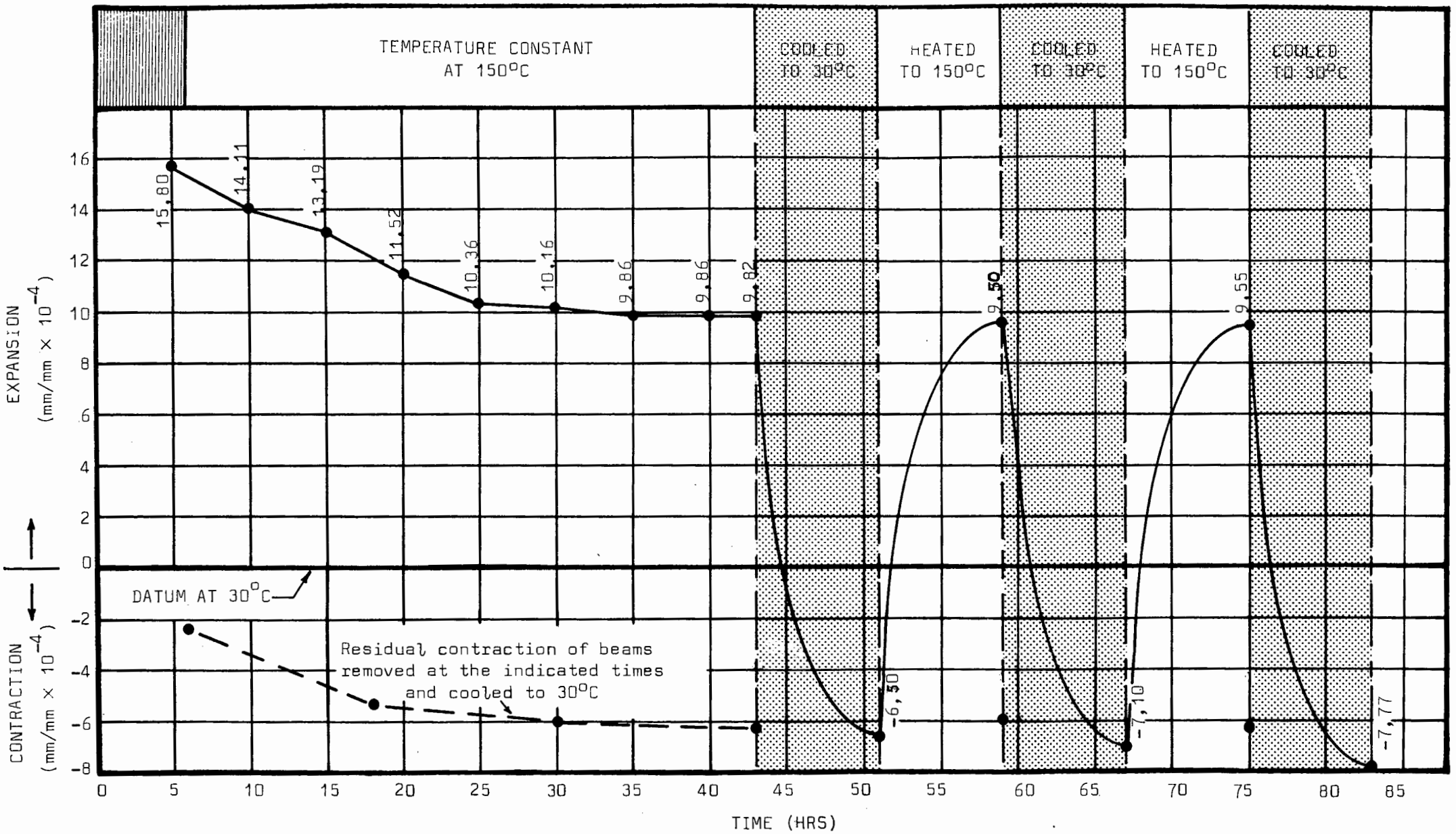

FIG.III.77: The linear deformation of test specimens which underwent drying at 150°C : Mix CMY.

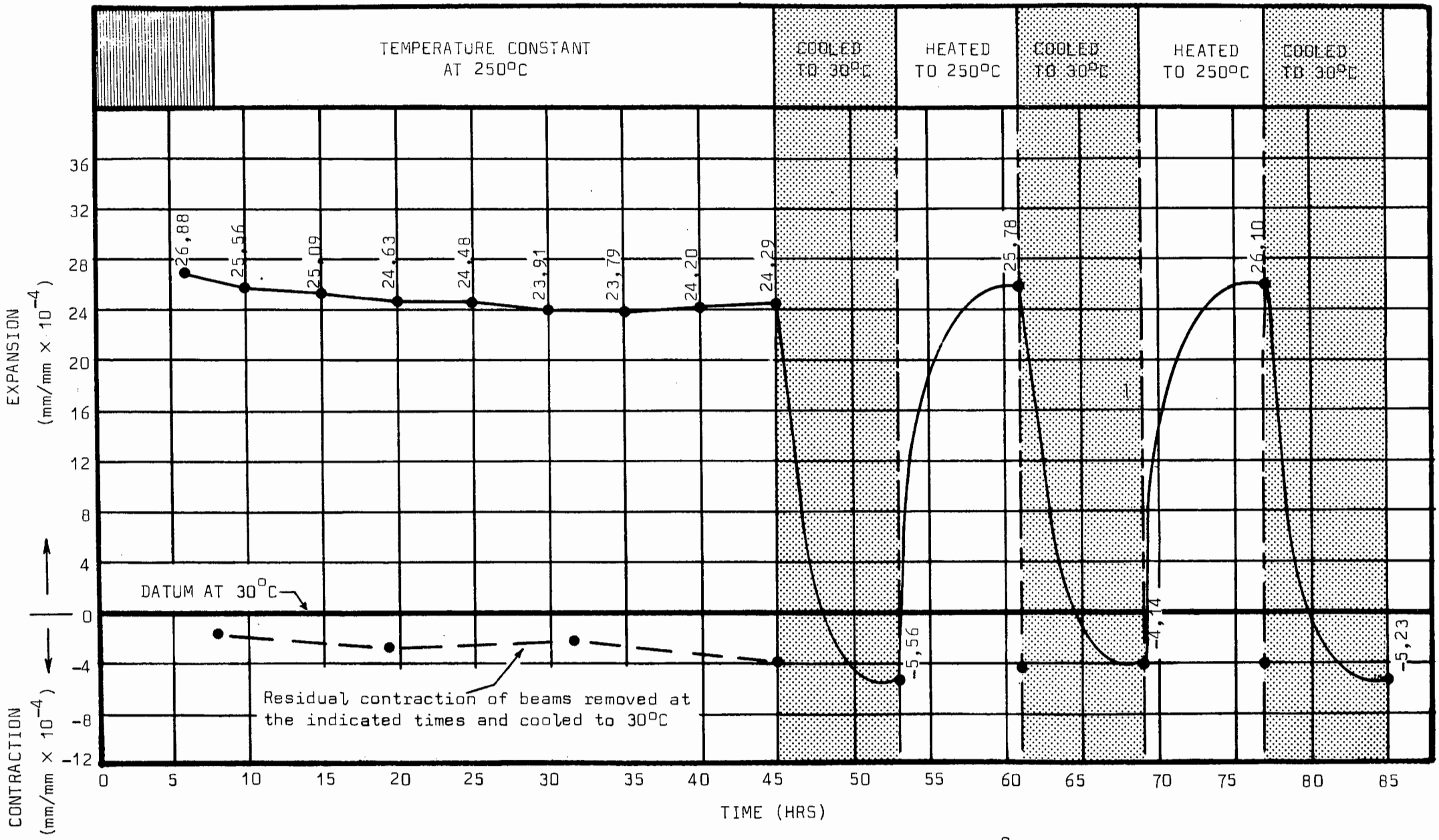

FIG.III.78: The linear deformation of test specimens which underwent drying at 250°C : Mix CMY.

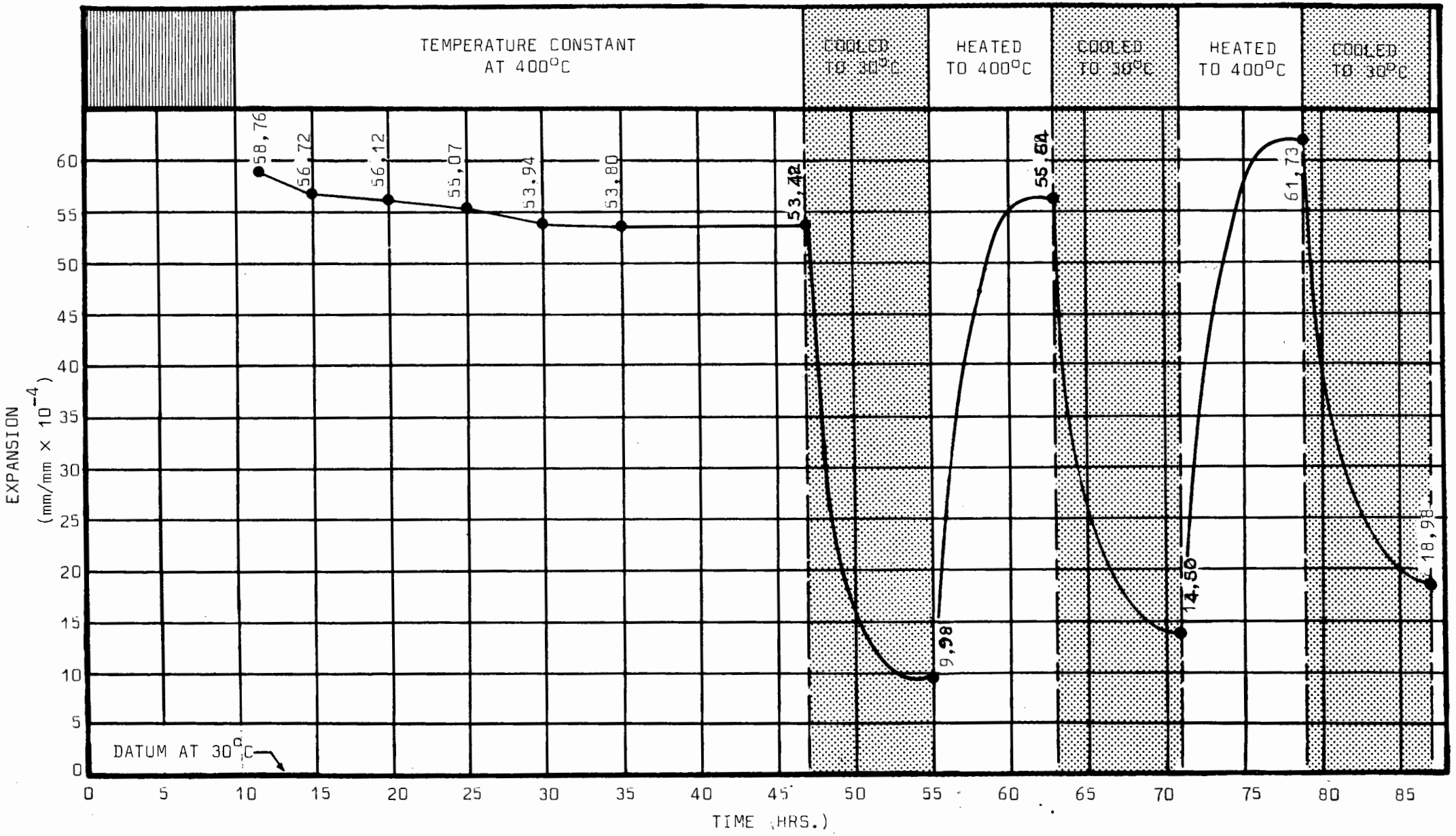

FIG.III.79: The linear deformation of test specimens which underwent drying at 400°C : Mix CMY.

(i) the linear deformation of the test specimens at the particular test temperature, or

(ii) the linear deformation of test specimens after cooling to the 30°C datum temperature.

i.e. no values of linear deformation are given at temperatures intermediate between the 30°C datum temperature and the test temperature. Also, to simplify plotting of the linear deformation graphs, the cooling cycle and heating cycle time periods are shown as being the same for all the test temperatures. This was not the case in the experimental work, i.e. the cooling time periods and heating time periods were dependent upon the test temperatures; in most instances these time periods * differed from the time period chosen to represent temperature cycling on the graphs.

Also shown in Figure III.73 to Figure III.79, and in Figure A.IV.1 to Figure A.IV.42 in APPENDIX IV, are the values of residual linear deformation determined on test specimens which were removed from Furnace No. 2 (Waterbath No. 2 at various times during the heating period and cooled to the datum temperature before testing. (These results were discussed in CHAPTER 7.) It is apparent that the residual linear deformation measured on these test specimens is usually in good agreement with the residual linear deformation of the test specimen on which linear deformation was continuously monitored during heating and subsequent temperature cycling.

The linear deformation curves of test specimens made from the various concrete mixes and tested at the different temperature levels are summarised in Figure III.80, Figure III.81 and Figure III.82. Figure III.80 illustrates the linear deformation of specimens made from the concrete mix BCY and tested at temperatures of 70°C (specimen fully saturated) 100°C (specimen fully saturated), 70°C (specimen allowed to dry), 100°C (specimen allowed to dry), 150°C (dry), 250°C (dry) and 400°C (dry). Figure III.81 and Figure III.82 show the data for the concrete mixes CCX and CCY respectively, and Figure III.83, Figure III.84 and Figure III.85 the data for the mortar mixes BMY, CMX and CMY respectively. In order to facilitate comparison of the linear deformation curves for specimens of a particular mix tested at the various test temperatures, the values of linear expansion during heating are plotted so that the end of the heating period occurs at 47 hours, i.e. the origin of the time axis on Figure III.80 to Figure III.85 applies only to the linear deformation of specimens heated to 400°C; for all the other test temperatures the origin of the time axis is between 2 hours and 6 hours, depending on the temperature level. Also, the cooling and

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* The cooling rates and heating rates are given in PART II, CHAPTER 3.

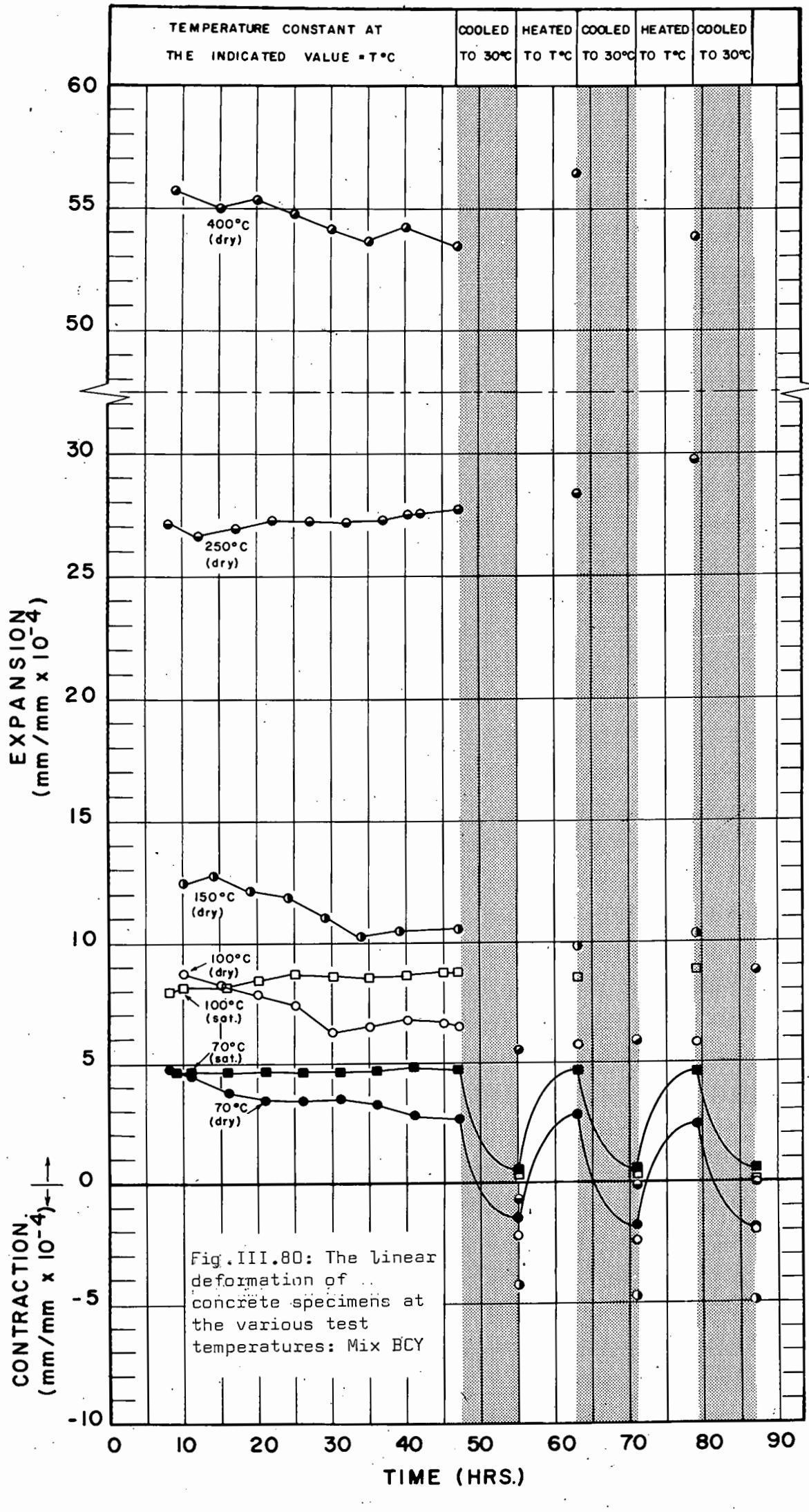

Fig.III.80: The linear deformation of concrete specimens at the various test temperatures: Mix BCY

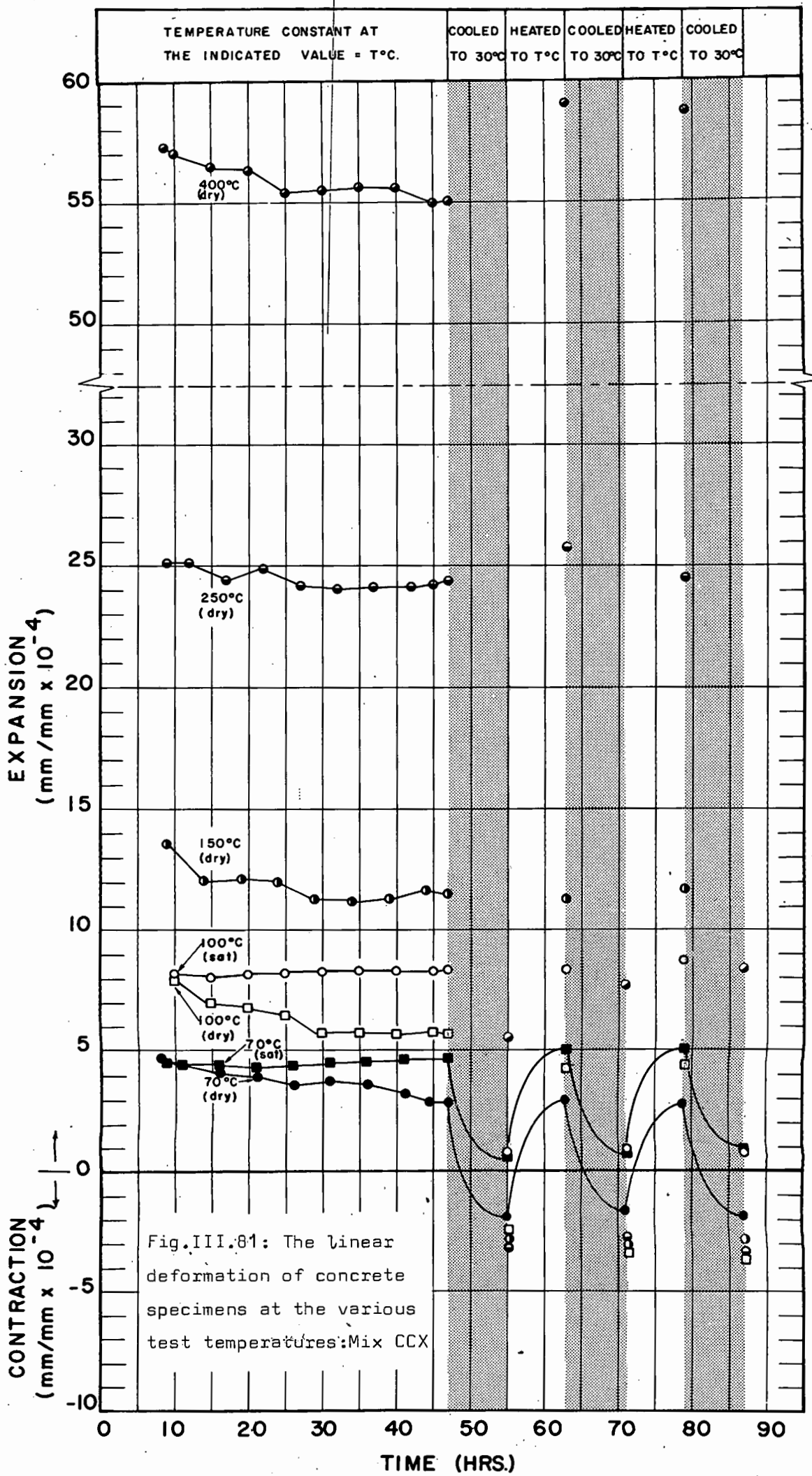

Fig.III.81: The linear deformation of concrete specimens at the various test temperatures:Mix CCX

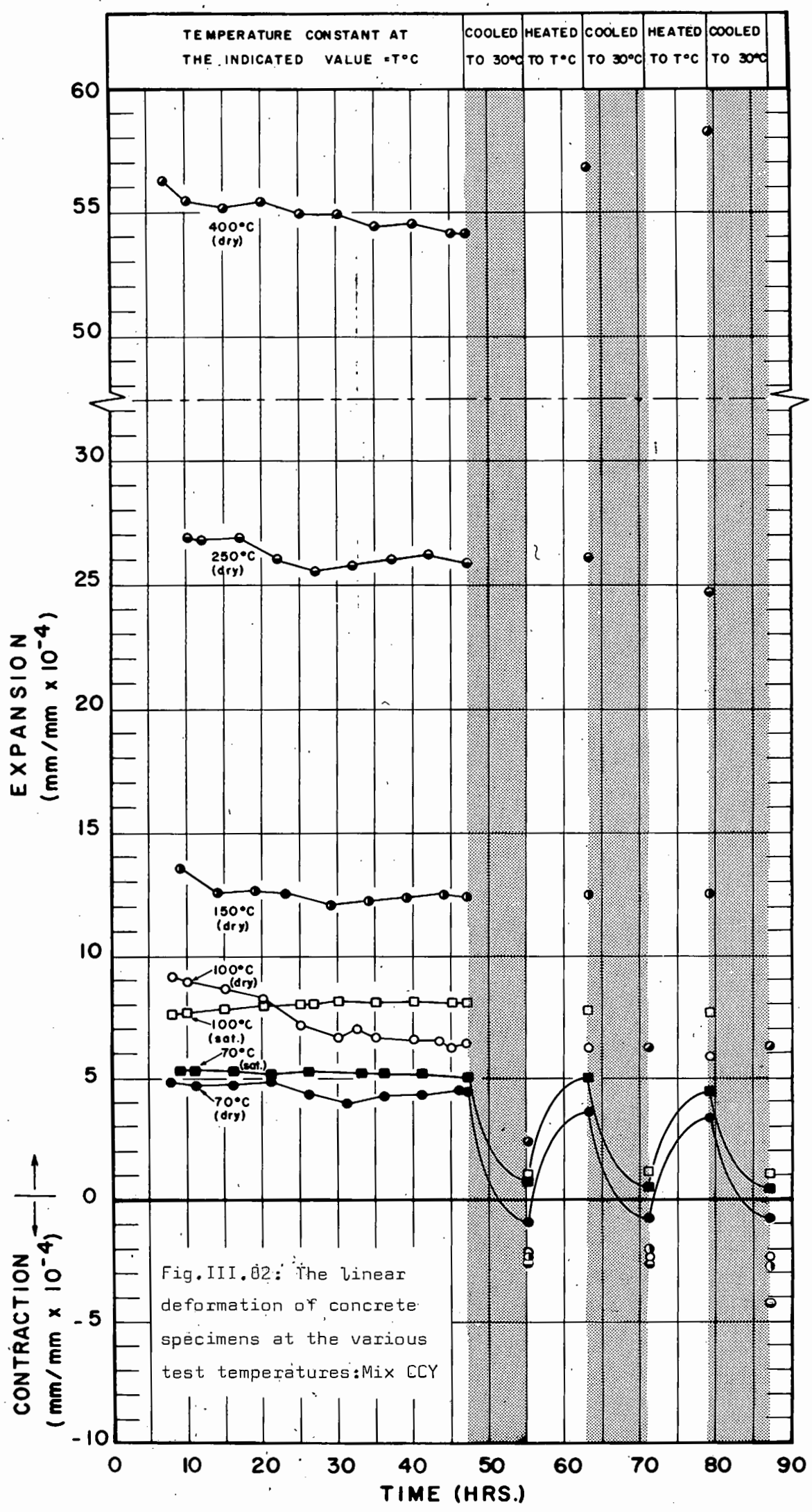

Fig.III.82: The linear deformation of concrete specimens at the various test temperatures:Mix CCY

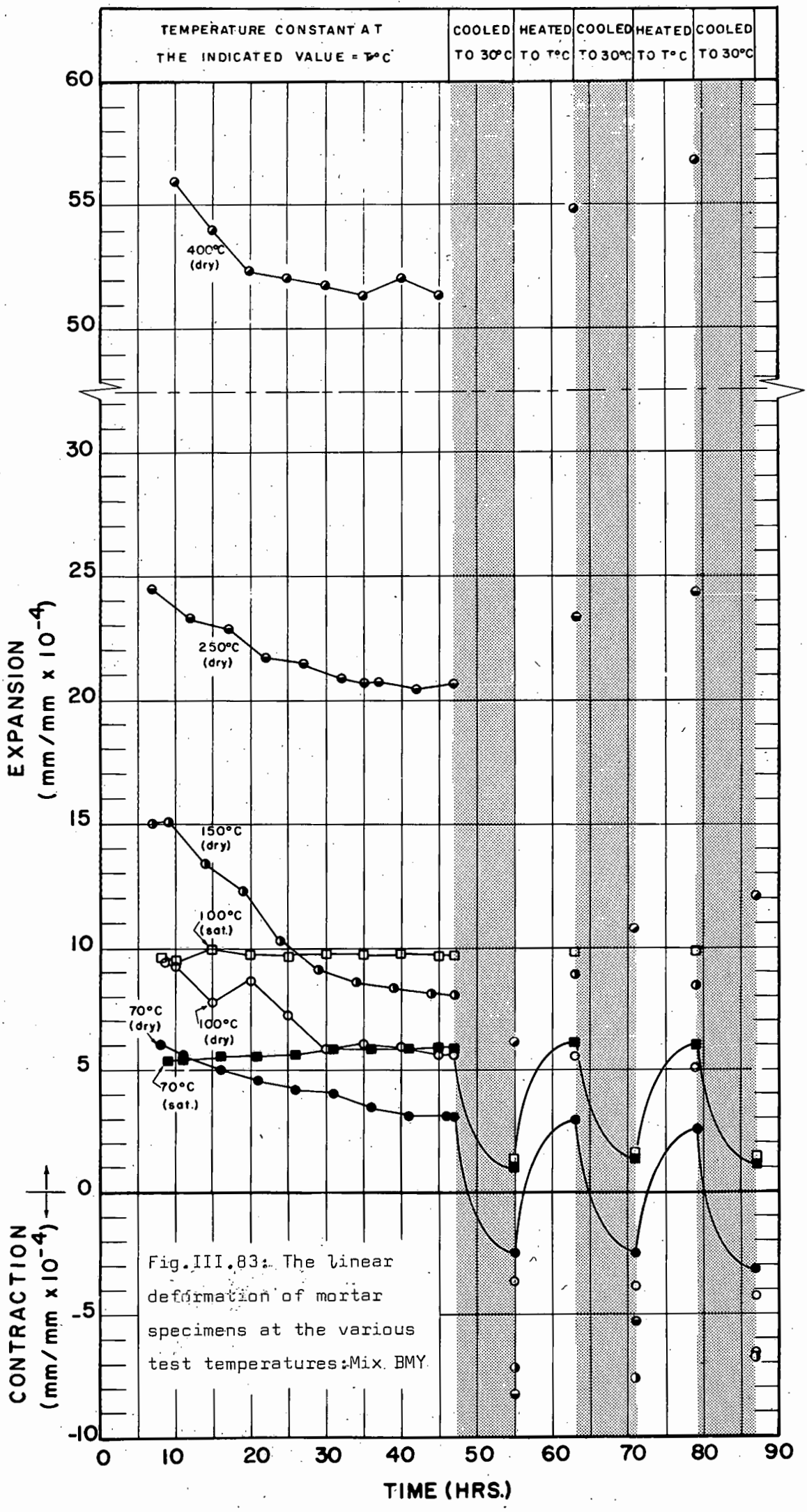

Fig.III.83: The linear deformation of mortar specimens at the various test temperatures: Mix. BMY

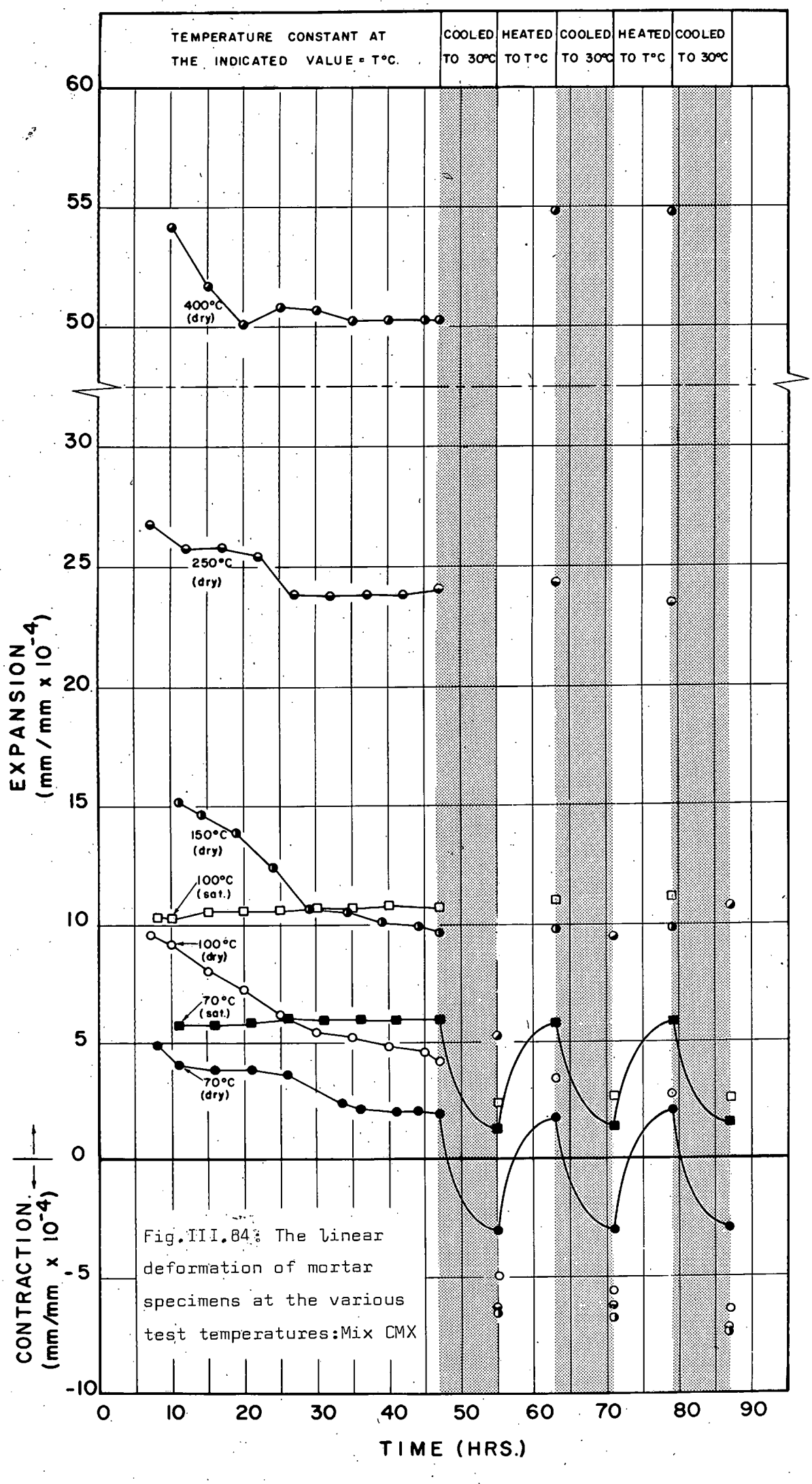

Fig.III.84: The linear deformation of mortar specimens at the various test temperatures: Mix CMX

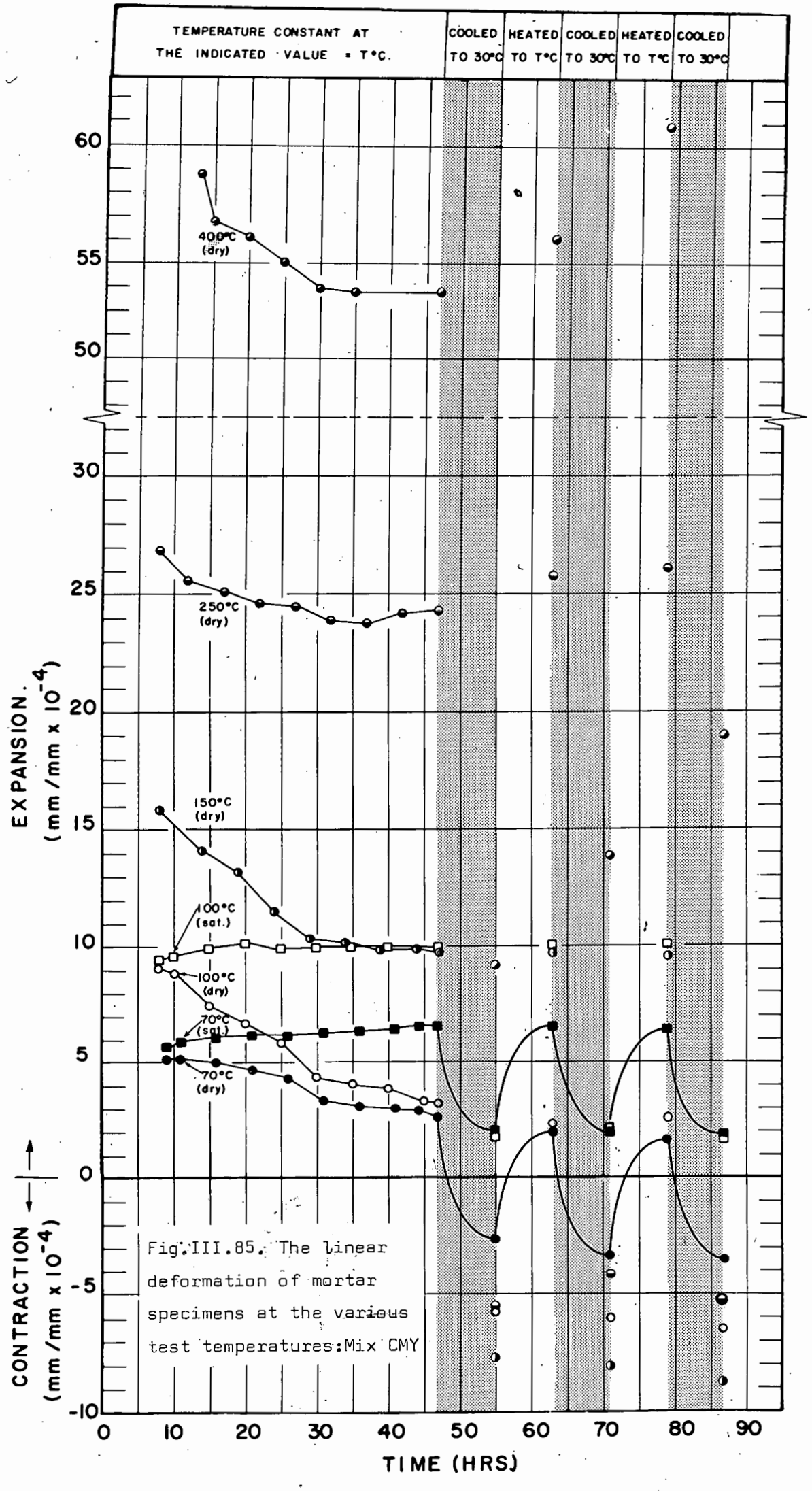

Fig. III.85. The linear deformation of mortar specimens at the various test temperatures: Mix CMY

heating curves of linear deformation for test specimens during temperature cycling are illustrated only for;

(i) specimens which remained fully saturated at a test temperature of 70°C, and

(ii) specimens which underwent drying at 70°C.

The measured values of residual deformation for test specimens cooled from higher temperature levels are plotted, but the cooling and heating curves during temperature cycling are not shown. The values can be identified by referring to the symbol that was used to plot the linear deformation during the heating period prior to temperature cycling.

8.1 Changes in the Linear Deformation of Test Specimens during the Heating Period Prior to Temperature Cycling

It is apparent from the data shown in APPENDIX IV, Figure A.IV.1 to Figure A.IV.42, and summarised in Figure III.80 to Figure III.85 that:

(i) The linear expansion of concrete and mortar test specimens which remained fully saturated at temperatures of either 70°C or 100°C exhibits a gradual increase during the time that the temperature remained constant at the test temperature level. The increase in linear deformation during the heating period is widely different for the various concrete and mortar mixes. Furthermore, there is no definite trend as to whether the increases are greater for the concrete mixes or the mortar mixes. This is probably because part of the increase in linear expansion occurred during the time period when the test specimens were being heated to the test temperature.

(ii) The linear expansion of concrete and mortar specimens which underwent drying at temperatures of either 70°C, 100°C, 150°C, 250°C or 400°C, usually decreases during the period when the temperature was constant at the test temperature level, i.e. the specimen underwent shrinkage during this period. The change in linear expansion was more pronounced for mortar mixes than for the concrete mixes, particularly at temperatures above 100°C; at these temperatures the reduction in linear expansion of the mortar specimens was always at least twice as great as the reduction in the linear expansion of the concrete test specimens. The difference between the shrinkage

of the mortar and concrete test specimens is to be expected, since,

(a) the mortar specimens do not contain coarse aggregate which offers restraint against shrinkage, and

(b) there is a smaller volume of mortar in the concrete specimens than in the mortar test specimens.

From the experimental results it appears that the greatest reduction in linear expansion occurs at temperatures of 100°C and 150°C. However, this cannot be stated with certainty since some shrinkage could possibly have occurred during the time period when the test specimen was being heated to the test temperature level. Consequently, the residual values of linear defomration (i.e. the linear deformation of specimens cooled to the datum temperature) give a better indication of the extent of the shrinkage at the various temperature levels.

8.2 The Residual Linear Deformation of Test Specimens after Cooling to the Datum Temperature

The data shown in Appendix IV, Figure A.IV.1 to Figure A.IV.42, and summarised in Figure III.80 to Figure III.85, indicate that the mortar and concrete test specimens always exhibit either a residual contraction or a residual expansion when cooled to the datum temperature. A residual expansion occurs in concrete and mortar test specimens which remained fully saturated whilst heated to temperatures of either 70°C or 100°C. Table III.10 shows the mean value of the residual expansion values measured at the end of each cooling cycle, i.e. the mean of three values for every mix.

TABLE III.10

The mean value of residual expansion for test specimens cooled from temperatures of 70°C and 100°C respectively

	Mix Name	Mean residual expansion of test specimens cooled from 70°C (mm/m)	Mean residual expansion of test specimens cooled from 100°C (mm/m)
CONCRETE MIXES	BCY	0,059	0,040
	CCX	0,077	0,079
	CCY	0,055	0,107
MORTAR MIXES	BMY	0,128	0,148
	CMX	0,142	0,255
	CMY	0,188	0,184

It is apparent from Table III.10 that at temperatures of both 70°C and 100°C the residual expansion of mortar test specimens is approximately twice as great as the residual expansion of the corresponding concrete specimens. Consequently, it appears that the residual expansion is the result of a change which occurs within the mortar. Furthermore, it appears that the residual expansion of concrete and mortar test specimens cooled from 70°C is in most instances approximately the same as the residual expansion of test specimens cooled from 100°C. The exceptions to this were the concrete mix CCY and the mortar mix CMX; for these mixes the residual expansion of the test specimens cooled from 100°C is almost twice as great as the residual expansion which occurred for specimens cooled from 70°C.

Concrete and mortar test specimens which underwent drying during heating always exhibit a residual contraction when cooled from temperatures of either 70°C, 100°C or 150°C. The residual contraction of specimens cooled from 150°C was larger than the residual contraction of specimens cooled from the lower temperature levels. Concrete and mortar test specimens cooled from 250°C usually exhibit a residual contraction. However, Figure III.80 to Figure III.85 show that the residual contraction is usually less than or approximately the same as, the residual contraction which occurred for mortar and concrete test specimens cooled from 150°C.

Test specimens cooled from 400°C always exhibit a residual expansion. The residual expansion of the mortar specimens is always greater than the residual expansion of the corresponding concrete test specimens. This is illustrated in Table III.11 which shows the residual expansion of test specimens at the end ofeach of the heating/cooling cycles from 400°C. Table III.11 shows, too, that the residual expansion of test specimens cooled from 400°C increases with successive heating/cooling cycles. In most instances the residual expansion after two additional heating and cooling cycles is approximately twice as great as the residual expansion which occurred when test specimens were first cooled from 400°C

TABLE III.11

The residual expansion of test specimens after successive heating/cooling cycles from 400°C

	Mix Name	RESIDUAL EXPANSION (mm/m)		
		After 1st Cooling from 400°C	After 1 Add. Heating/ Cooling Cycle	After 2 Add. Heating/ Cooling Cycles
CONCRETE MIXES	BCY	0,552	0,589	0,879
	CCX	0,554	0,771	0,838
	CCY	0,235	0,625	0,626
MORTAR MIXES	BMY	0,616	1,084	1,218
	CMX	0,524	0,945	1,075
	CMY	0,918	1,372	1,898

8.3 The Coefficient of Thermal Expansion of the Various Concrete and Mortar Mixes

The coefficient of thermal expansion is calculated from the change in linear deformation which occurred when test specimens were cooled from the test temperature to the datum temperature, e.g. from Figure III.73 (the linear deformation of the mortar mix CMY, fully saturated at 70°C) the coefficient of thermal expansion is;

$$\frac{6,59 - 1,89}{40} \times 10^{-4} \text{ mm/mm deg C.}$$

$$= 11,75 \times 10^{-6} \text{ mm/mm deg C.}$$

The coefficient of thermal expansion during successive heating/cooling cycles may be calculated in a similar manner.

The coefficient of thermal expansion of the various concrete and mortar mixes at the different temperature levels are shown in Table III.12. In order to illustrate the results graphically, a mean coefficient of thermal expansion is calculated from the three values of thermal expansion obtained during the three successive cooling cycles. This approach is not strictly correct as the coefficient of thermal expansion between successive temperature cycles may differ significantly due to either:

(i) further water loss during temperature cycling, or

(ii) progressive microcracking of test specimens during successive temperature cycling.

It would appear the the influence of (i) and (ii) above on the coefficient of thermal expansion is taken into account by the corresponding change which occurs in the residual contraction/expansion of test specimens. However, this cannot be stated with certainty since the results shown in Table III.12 indicate that in some instances the coefficient of thermal expansion of test specimens does change markedly between successive temperature cycles. It is not possible to determine whether these variations are due to random fluctuations or due to a significant change in thermal expansion. This is because the experimental error in determining the coefficient thermal expansion could have caused variation between successive determinations of approximately 5% at 70°C *, 4% at 100°C and decreasing to 2,4% at 400°C. Since the variation between the three values of thermal expansion determined during successive

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* This error is due to the possible error in temperature measurement, viz: The Cu/Const. thermocouples had an accuracy of 1%. Consequently, at 70°C the error could be 0,7 deg C and at 30°C the error could be 0,3 deg C. The total error for one determination of the coefficient of thermal expansion could thus be 1,0 deg C. The temperature difference is (70°C - 30°C) = 40 deg C and consequently the error due to temperature measurement could equal 2,5%. Hence, the error between two successive determinations of the coefficient of thermal expansion at 70°C could have been 2,5% x 2 = 5,0%. (This does not include the possible error in the linear deformation measurement of test specimens.)

	THERMAL EXPANSION (mm/mm × 10^{-6} per deg.C)						
	Test Temperature						
	70° SAT	70° DRY	100°SAT	100° DRY	150° DRY	250° DRY	400° DRY
MIX BCY							
1st Cool	10,35	10,28	11,03	12,42	12,34	12,88	12,88
2nd Cool	10,12	11,83	10,71	11,65	12,15	12,82	13,30
3rd Cool	10,20	10,72	11,07	10,82	12,68	13,10	12,91
Mean	10,22	10,94	10,94	11,63	12,39	12,93	13,03
MIX CCX							
1st Cool	10,22	11,81	10,86	11,82	11,90	12,44	13,02
2nd Cool	10,40	11,64	10,77	10,81	12,04	13,07	13,51
3rd Cool	10,50	11,80	11,14	11,40	12,13	12,71	13,24
Mean	10,37	11,75	10,92	11,34	12,02	12,74	13,26
MIX CCY							
1st Cool	10,72	13,34	11,04	12,25	12,27	12,93	13,64
2nd Cool	11,21	10,98	10,82	11,80	11,94	13,05	13,31
3rd Cool	10,10	11,24	10,87	11,74	12,71	13,18	13,69
Mean	10,68	11,85	10,91	11,93	12,31	13,05	13,55
MIX BMY							
1st Cool	12,21	13,38	11,99	13,20	13,43	13,13	11,90
2nd Cool	11,89	12,65	11,83	13,46	13,87	13,35	11,59
3rd Cool	11,73	12,98	12,09	13,38	13,73	14,07	11,74
Mean	11,94	13,00	11,97	13,35	13,68	13,52	11,74
MIX CMX							
1st Cool	11,64	12,35	11,89	13,14	13,46	13,81	11,84
2nd Cool	11,02	11,98	12,02	12,93	13,79	13,90	11,94
3rd Cool	10,79	12,68	12,26	13,15	14,26	14,05	11,58
Mean	11,15	12,34	12,06	13,07	13,84	13,92	11,79
MIX CMY							
1st Cool	11,75	13,19	11,51	13,61	13,60	13,57	11,74
2nd Cool	11,43	13,22	11,62	13,17	13,84	13,60	11,12
3rd Cool	11,35	12,87	11,79	12,99	14,43	14,24	11,25
Mean	11,51	13,09	11,64	13,26	13,96	13,80	11,37

TABLE III.12: The coefficient of thermal expansion of the various concrete and mortar mixes at the different test temperatures.

temperature cycles is usually not as large as the variations which could have occurred due to experimental error, the mean of the three thermal expansion values is taken as the best approximation to the thermal expansion of a test specimen.

The coefficient of thermal expansion at the various test temperatures is shown in Figure III.86 for the concrete mix BCY and the corresponding mortar mix BMY. Figure III.87 illustrates the data for the concrete mix CCX and mortar mix CMX, and Figure III.88 the data for mixes CCY and CMY. Also shown in Figure III.86 to Figure III.88 is the coefficient of thermal expansion of the coarse aggregate * and the fine aggregate * at the various temperature levels.

It is apparent from the average coefficients of thermal expansion plotted in Figure III.86 to Figure III.88 that for test specimens which underwent drying during heating:

(i) The coefficient of thermal expansion of the various concrete mixes always increases as the temperature level increases. However, the increase in the coefficient of thermal expansion between the 250°C and the 400°C temperature levels is not as great as the increase in thermal expansion between the 100°C and 250°C temperature levels. Values of the coefficient of thermal expansion range from approximately 11,0 mm/mm deg C. at 70°C to 13,4 mm/mm deg C. at 400°C.

(ii) The coefficient of thermal expansion for the various mortar mixes tends to increase as the test temperature level increases only up to a test temperature of 150°C. At 150°C the coefficient of thermal expansion of mortar test specimens is always higher than the coefficient of thermal expansion of corresponding concrete test specimens. Values for the mortar range between 13,6 mm/mm deg C. and 13,9 mm/mm deg C., and those for the concrete mixes range from 12,0 mm/mm deg C. to 12,4 mm/mm deg C.

(iii) At 250° the coefficient of thermal expansion of mortar test specimens is approximately the same as the coefficient of thermal expansion of mortar specimens at 150°C. However, the coefficient of thermal expansion of the mortar specimens at 250°C is always larger than the coefficient of thermal expansion of the corresponding concrete test specimens at 250°C.

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* These values of thermal expansion are from work done in this laboratory - reference 74. The values of thermal expansion above 300°C are shown as a broken line since they were extrapolated from the values at 250°C and 300°C.

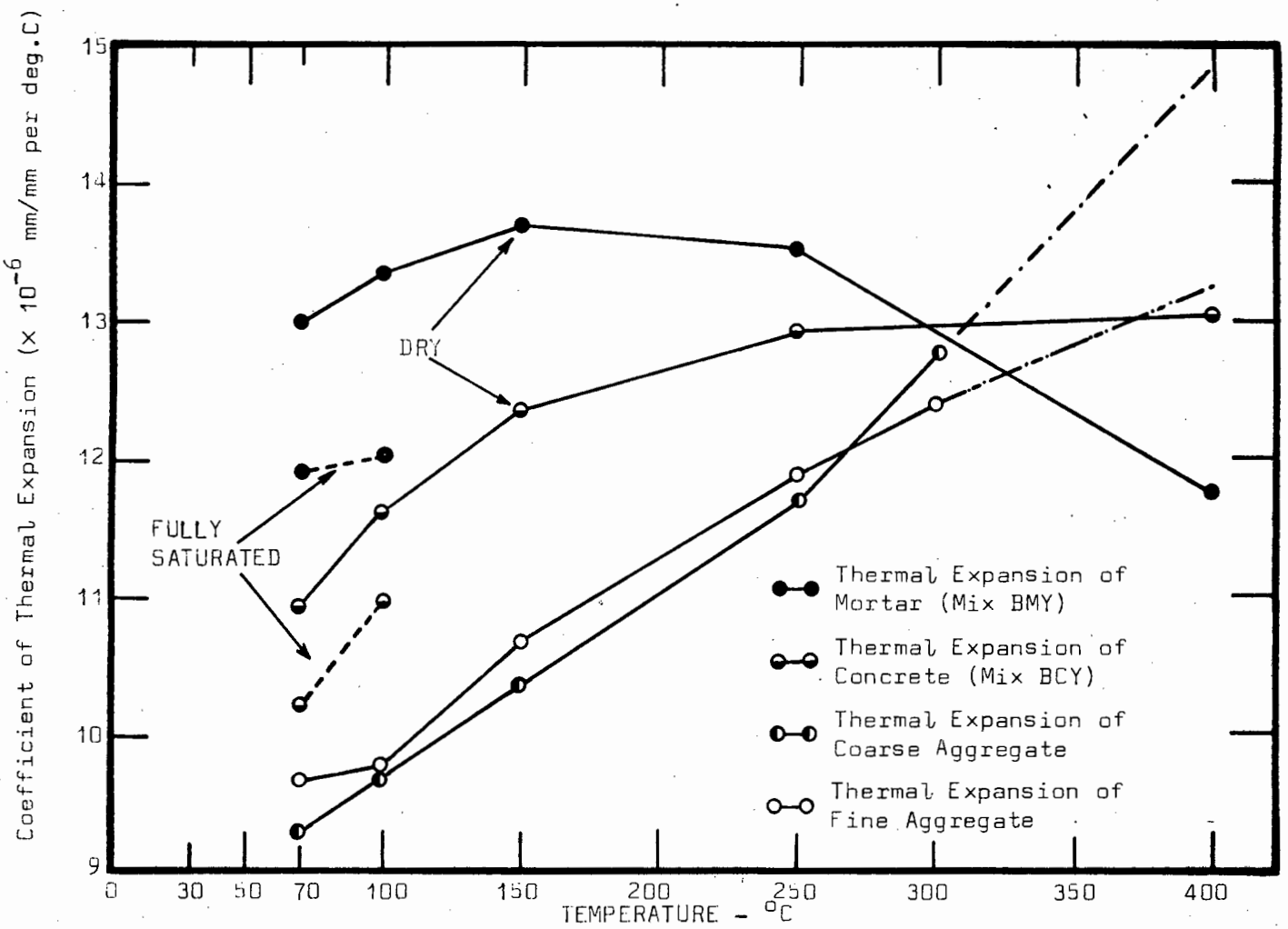

FIG.III.86: The coefficient of thermal expansion at various test temperatures: Mixes BCY and BMY.

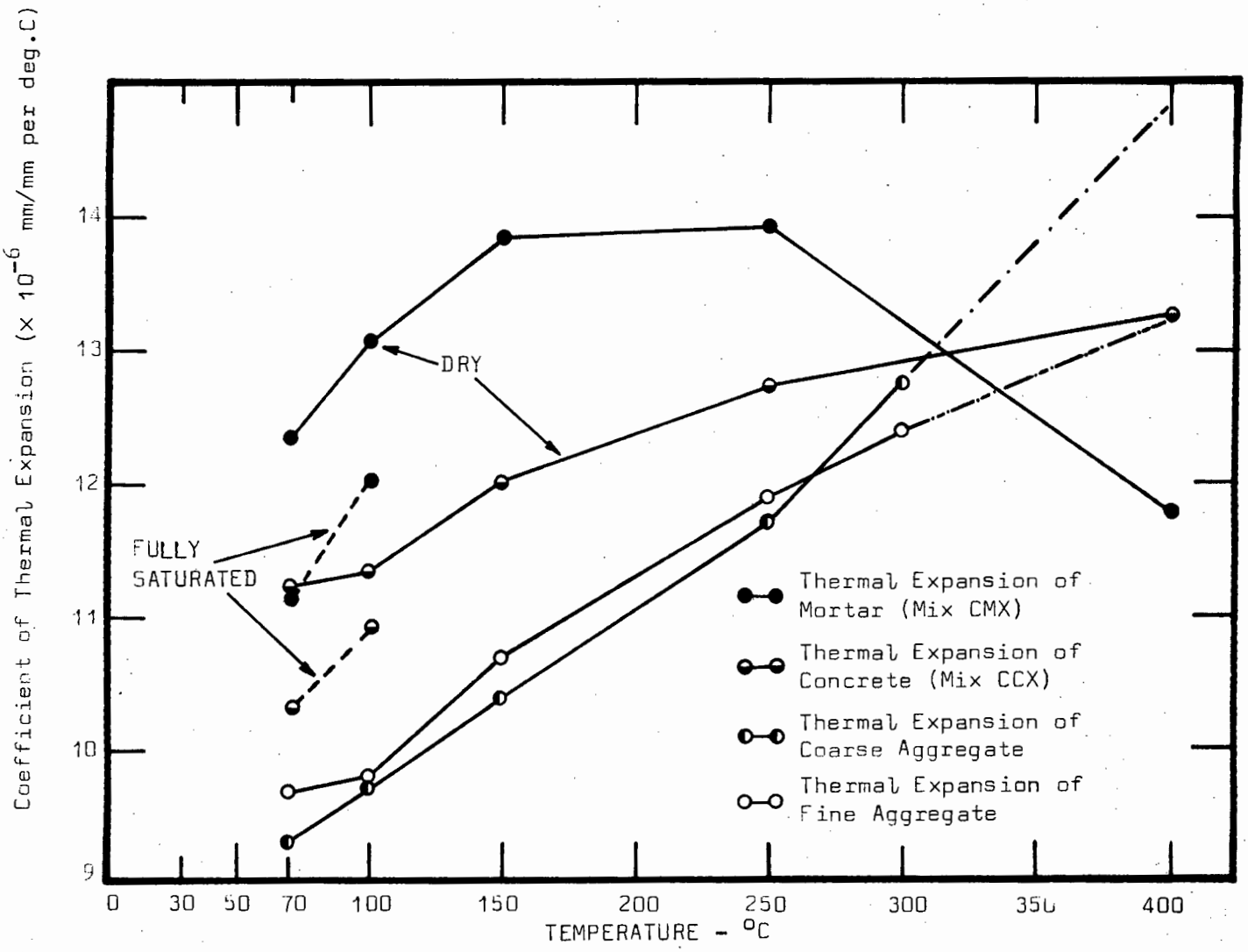

FIG.III.87: The coefficient of thermal expansion at various test temperatures: Mixes CCX and CMX.

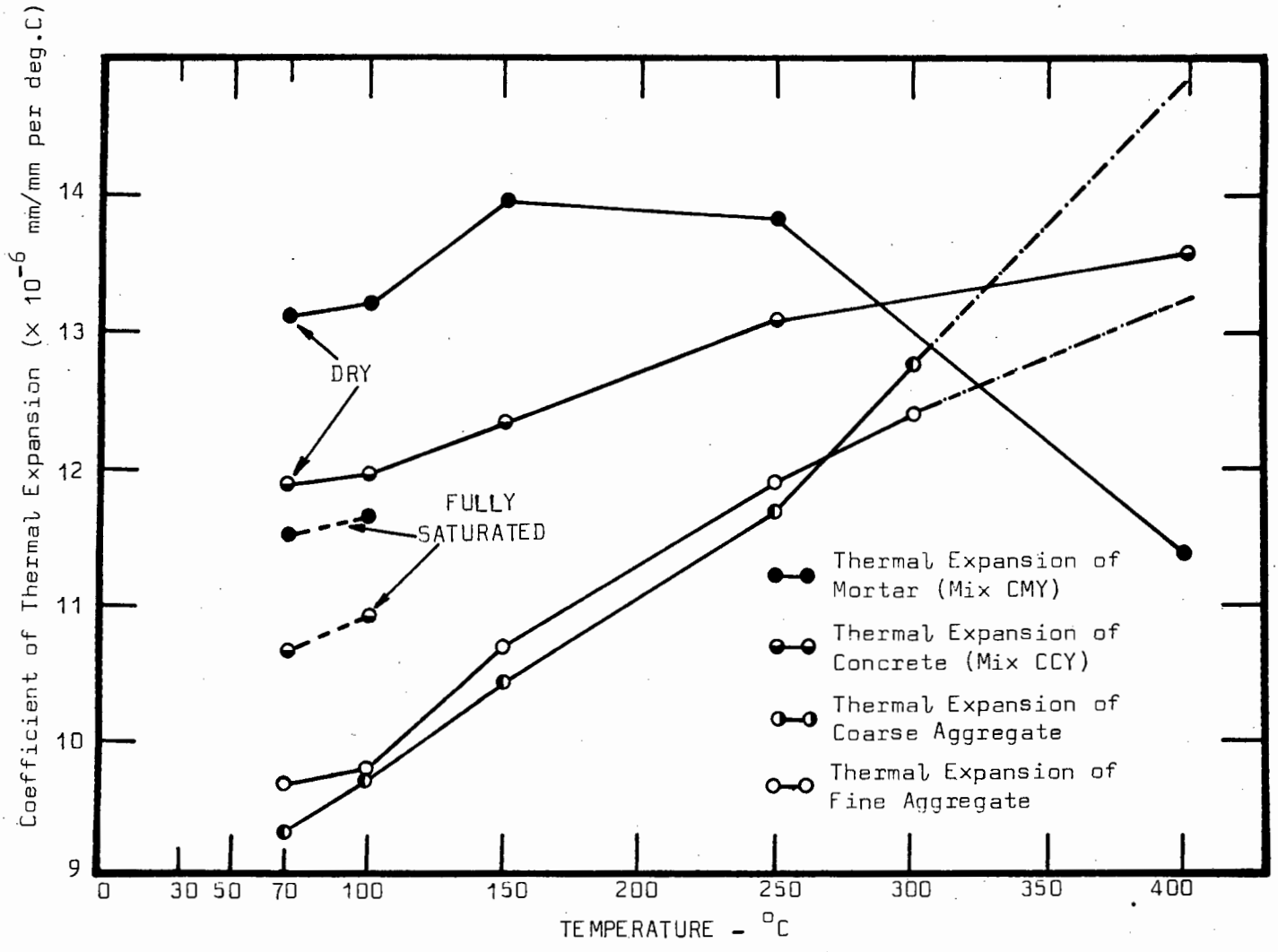

FIG.III.88: The coefficient of thermal expansion at various test temperatures : Mixes CCY and CMY.

(iv) At a temperature of 400°C, the coefficient of thermal expansion of the specimens made from the mortar mixes is markedly lower than the values at either 250°C or 150°C. Furthermore, mortar test specimens at 400°C have a lower coefficient of thermal expansion than concrete test specimens at 400°C. Values of the coefficient of thermal expansion at 400°C range from 11,4 mm/mm deg C. to 11,8 mm/mm deg C. for mortar specimens and from 13,0 mm/mm deg C. to 13,5 mm/mm deg C. for the corresponding concrete test specimens.

The data shown in Figure III.86 to Figure III.88 for the test specimens which remained fully saturated during heating indicate that:

(i) Mortar test specimens heated to 70°C have a coefficient of thermal expansion which is approximately 10% lower than the coefficient of thermal expansion of mortar test specimens which underwent drying at 70°C. Values of the coefficient of thermal expansion range between 11,2 mm/mm deg C. and 11,9 mm/mm deg C.

(ii) Concrete test specimens which remained fully saturated at 70°C have a coefficient of thermal expansion which is between 5% and 10% lower than the coefficient of thermal expansion of concrete test specimens which underwent drying at 70°C. Values of the coefficient of thermal expansion for saturated specimens range from 10,2 mm/mm deg C. to 10,7 mm/mm deg C. These values are lower, too, than the values of coefficient of thermal expansion for test specimens made from the corresponding mortar mixes.

(iii) Mortar test specimens which remained fully saturated at 100°C have a coefficient of thermal expansion which is higher than the coefficient of thermal expansion of saturated mortar specimens at 70°C. However, for two of the three mortar mixes the difference between the coefficient at 70°C and 100°C was less than 1%. The coefficient of thermal expansion of mortar specimens which remain saturated at 100°C is approximately 10% lower than the coefficient of thermal expansion of test specimens which underwent drying at 100°C.

(iv) Concrete test specimens which remained fully saturated at 100°C have a coefficient of thermal expansion which is higher than the coefficient of thermal expansion of saturated concrete specimens heated to 70°C. For the concrete mix CCY the difference between the thermal expansion at 70°C and 100°C was approximately 3,5% whereas for concrete mix CCX

the difference was 5%, and for mix BCY 8%. The coefficient of thermal expansion of saturated concrete specimens at 100°C is between 3% and 8% lower than the coefficient of thermal expansion of specimens which underwent drying at 100°C.

The data shown in Figure III.86 indicate that the coefficient of thermal expansion of both the coarse aggregate and the fine aggregate increases as the test temperature increases. The coarse aggregate and fine aggregate exhibit very similar thermal expansion coefficients up to a temperature of 250°C. Above this temperature level the coarse aggregate shows a greater increase in thermal expansion with temperature than the fine aggregate. The large difference between the coefficient of thermal expansion of the coarse aggregate and fine aggregate at 400°C is a possible reason why the coefficient of thermal expansion of concrete specimens at 400°C is greater than the coefficient of thermal expansion of mortar specimens at 400°C. However, this does not explain why the coefficient of thermal expansion of mortar specimens is greater at 250°C than at 400°C. It appears from the results that mortar test specimens undergo cracking when cooled from 250°C to the datum temperature. Consequently, the measured residual contraction of mortar specimens cooled from 250°C is not as great as the residual contraction of mortar specimens cooled from 150°C. Hence the coefficient of thermal expansion is lower for mortar specimens at 250°C than for mortar specimens heated to 150°C. The cracking is more severe for mortar specimens cooled from 400°C and results in a residual expansion of test specimens. Consequently, the coefficient of thermal expansion of mortar specimens is lower at 400°C than for specimens heated to 250°C. This explains, too, why the concrete test specimens exhibit a smaller increase in the coefficient of thermal expansion between 250°C and 400°C than the increase in the coefficient of thermal expansion between 100°C and 250°C.

PART IV

STATISTICAL ANALYSIS

1.1 INTRODUCTION

Statistical analyses of the results reported in PART III were performed on the following properties of test specimens made from the various mixes and tested at different times during the heating period or temperature cycling period:-

(i) residual linear deformation,
(ii) percentage water loss,
(iii) compressive strength,
(iv) ultrasonic pulse velocity,
(v) dynamic Young's modulus,
(vi) Poisson's ratio.

For the abovementioned properties separate analyses were carried out for the respective cases of;

(a) test specimens which were tested immediately after cooling to the datum temperature, and

(b) test specimens which were cooled and immersed in water for 7 days before testing.

In addition, an analysis was perfomred on the compressive strength results of test specimens which were tested whilst hot.

It should be noted that in all the analyses the dependent variable is always the change between the measured property value of a heated test specimen and the mean control value of the particular property, i.e. the actual changes which occurred in the various properties during the heating period - not the residual ratios of the various properties - are used in the analyses. In the case of the water loss and residual linear deformation data, the results reported in PART III are the changes which occurred and were consequently not modified. The change in compressive strength, ultrasonic pulse velocity, dynamic Young's modulus and Poisson's ratio respectively, was obtained by subtracting the mean control values of these properties from the respective property values determined on heated test specimens. These property changes

are referred to as the coded values of the particular property.

The statistical analysis was performed in the following stages:-

(i) Using analysis of variance [77; 78; 79; 80] it was determined whether the property changes (i.e. the coded values of a particular property) that occurred for test specimens made from the various mortar mixes (concrete mixes)* are significantly different for the specimens which were subjected to tests at the following test times:-

(a) The various times at which test specimens were removed from the furnace (waterbath) during the period when the test temperature remained constant, viz. the test times T hours, T + 12 hours, T + 24 hours and T + 36 hours, where T is the time at which the desired test temperature was attained.

(b) The various times during the temperature cycling period, viz. the test time T + 36 hours, T + 36 hours + 1 cycle and T + 36 hours + 2 cycles.

For both (a) and (b) above the analysis of variance also indicates whether the coded property values of test specimens made from the various mortar mixes (concrete mixes) are significantly different between mixes.

(ii) In instances where the abovementioned analysis of variance indicates that the coded values for a particular property of test specimens made from the mortar mixes (concrete mixes) are significantly different between the respective test times, it was determined whether the coded values either increase, decrease or exhibit no trend between successive test times. Consequently, it was ascertained whether the various properties either increase, decrease or remain constant during the heating periods (a) and (b) above.

(iii) In instances where the analysis of variance indicates that the coded property values of test specimens made from the various mortar mixes (concrete mixes) are significantly different between mixes, Tukey's method of pairwise comparison [77; 81] was used to compare the property changes exhibited by test specimens made from;

(a) the two mortar (concrete) mixes with mix proportions which

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* "Concrete mixes" written in parenthesis next to "mortar mixes" means that an exactly similar analysis was performed for the concrete mixes.

differed only in water content, viz. the mortar mixes BMY and CMX (the concrete mixes BCY and CCX), and

(b) the two mortar (concrete) mixes with mix proportions which differed only in volumetric concentration of aggregate, viz. the mortar mixes CMX and CMY (the concrete mixes CCX and CCY).

(iv) It was determined whether the coded values of a particular property for test specimens made from the concrete mixes are either greater than, less than, or equal to the coded values of that property for test specimens made from the mortar mixes, i.e. for a particular property the average coded property value for test specimens made from the various concrete mixes is compared to the average coded property value for test specimens made from the various mortar mixes. This analysis was performed using Tukey's method of multiple comparisons.[77; 81]

The results of the analyses for (i), (ii) and (iii) above are reported in CHAPTER 2, and the results of (iv) are given in CHAPTER 3.

1.2 Statistical methods

A computer programme was written to perform a fixed effects, two-way analysis of variance on data with or without replications. The information shown in Table IV.1 is derived from the mathematical model for a two-way analysis of variance. (77; 78; 79; 80)

TABLE IV.1

The layout for a two-way analyis of variance on data with replications

Source	Sum of Squares	Degrees of Freedom	Expected Mean Square	Error Mean Square
A treatment	$\hat{S}_1(Y)$	(NI-1)	$\hat{S}_1(Y)$	$s^2+JKs^2_A$
B treatment	$\hat{S}_2(Y)$	(NJ-1)	$\hat{S}_2(Y)$	$s^2+IKs^2_B$
A x B	$\hat{S}_3(Y)$	(NI-1)(NJ-1)	$\frac{\hat{S}_3(Y)}{(NI-1)(NJ-1)}$	$s^2+Ks^2_{AB}$
Error Residual	$\hat{S}_4(Y)$	NIxNJ(NK-1)	$\frac{\hat{S}_4(Y)}{(NIxNJ)(NK-1)}$	s^2
Total	$\sum_{i;j;k}(y_{ijk}-y_{...})^2$	NIxNJxNK-1		

where:

NI = the number of "A treatments"

NJ = the number of "B treatments"

NK = the number of replications at each "A treatment - B treatment" combination

Y_{ijk} = the observation of the dependent variable at the ith level of treatment A, the jth level of treatment B, and the kth replication of this treatment combination; i = 1, ..., NI; j = 1, ..., NJ; k = 1, ..., NK.

$$\hat{S}_1(Y) = NJ \times NK \sum_i (y_{i..} - y_{...})^2$$

$$\hat{S}_2(Y) = NI \times NK \sum_j (y_{.j.} - y_{...})^2$$

$$\hat{S}_3(Y) = NK \sum_{ij} (y_{ij.} - y_{i..} - y_{.j.} - y_{...})^2$$

(In these expressions the . in the subscript indicates averageing over the subscript wherever the . occurs)

$$S_A^2 = \frac{\sum_i (\alpha_i)^2}{(NI-1)}$$

$$S_B^2 = \frac{\sum_j (\beta_j)^2}{(NJ-1)}$$

$$S_{AB}^2 = \frac{\sum_{i;j} \gamma_{ij}}{(NI-1)(NJ-1)}$$

The hypotheses tested are;

$H_1 : \alpha_i = 0;$ $\quad i = 1, ..., NI$

$H_2 : \beta_j = 0;$ $\quad j = 1, ..., NJ$

$H_3 : \gamma_{ij} = 0;$ $\quad i = 1, ..., NI;$ $\quad j = 1, ..., NJ$

Each of the mean squares in Table IV.1 is independently distributed as χ^2. Consequently the coefficient formed by dividing the mean squares by the error mean square has Fisher's F distribution with the appropriate degrees of freedom. To test the hypotheses H_1, H_2 and H_3 respectively, the appropriate F-statistic is used e.g. to test hypothesis H_1, the value of $F_{(NI-1);\ NIxNJ(NK-1)}$ is determined from tables that give the distribution of the F statistic for a particular percentage level of significance.

In the abovementioned analysis provision was made to analyse data on which replicate tests had been carried out. All the statistical analyses were performed for;

(i) one replication of the water loss and residual linear deformation results,

(ii) two replications of the coded values of compressive strength, and

(iii) three replications of the coded values of ultrasonic pulse velocity, dynamic Young's modulus and Poisson's ratio results.

For cases (ii) and (iii) above, the replications were not carried out on independent test specimens. The replications refer to the repeat tests which were carried out on a particular test specimen *, viz. the values from which the mean results given in APPENDIX II, Table A.II.1 to Table A.II.42, were calculated. The results of the respective replicate tests on any of the properties mentioned in (ii) and (iii) above are not given owing to the large volume that these would occupy.

Consequently, for the coded values of a particular property determined from test specimens heated to a particular temperature, the analysis of variance is performed such that:

(i) The "A treatments" (referring to Table IV.1) are the various test times at which property measurements were made.

(ii) The "B treatments" (referring to Table IV.1) are the various concrete mixes (mortar mixes) from which test specimens were made.

(iii) The replications are as explained above.

If it is found from the analysis of variance that the coded values of a particular property are significantly different between tests performed at the respective test times, i.e. the "A effects" are significant, it has to be ascertained whether;

(i) the respective changes in the property increase with test time, or

(ii) the respective changes in the property decrease with test time, or

(iii) the respective changes in the property neither increase nor decrease with test time, i.e. despite the fact that the analysis of variance indicates that the respective coded values of the property are significantly different between test times, there is no trend to the changes which occurred at the various test times.

This is done by performing a linear regression analysis on the mean coded property values which occurred for the three concrete mixes (mortar mixes) at the respective test times. For a particular property the mean coded value which occurred at the first test time, i.e. at the first level of "treatment A",

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* This procedure was adopted after consulting the Department of Mathematical Statistics at the University of Cape Town.

is the value of (referring to the nomenclature given for Table IV.1)

$$\frac{\left[\sum_{j=1}^{NJ}\left(\sum_{k=1}^{NK} Y_{ijk}\right)\right]}{NJ \times NK} \qquad \text{for } i = 1.$$

Consequently, the mean coded value which occurred for the various mixes tested at the second, third and fourth test times, i.e. the second, third and fourth levels of "treatment A", is given by

$$\frac{\left[\sum_{j=1}^{NJ}\left(\sum_{k=1}^{NK} Y_{ijk}\right)\right]}{NJ \times NK} \qquad \text{for } i = 2;\ 3;\ \text{and } 4 \text{ respectively.}$$

The trend exhibited by the mean coded values between successive test times is determined by a regression analysis of the mean coded value against time. In this analysis the regression coefficient (m) and the standard error of the regression coefficient (m') is calculated. The trend indicated by the slope of the line of best fit through the mean coded values is accepted if

$$|m| > m'$$

i.e. if the trend indicated by the worst possible line through the mean coded values is similar to the trend indicated by the line of best fit, the trend is accepted as significant.

If it is found from the analysis of variance that the coded values of a particular property are significantly different between the respective concrete mixes (mortar mixes), i.e. that the "B" effects are significant, it may be ascertained whether;

(i) the coded values exhibited by the respective mixes are all significantly different, or

(ii) the coded values exhibited by the respective mixes are significantly different for only certain of the mixes.

This may be done by averaging the coded values of a particular property over the different test times and comparing the mean coded values of the respective mixes. The mean coded value for the first mix, i.e. at the first level of "treatment B", is the value of (referring to the nomenclature given for Table IV.1)

$$\left[\frac{\sum_{i=1}^{NI}\left(\sum_{k=1}^{NK} Y_{ijk}\right)}{NI \times NK}\right] \quad \text{for } j = 1.$$

For the second and third mixes, i.e. the second and third levels of "treatment B", the mean coded value is given by;

$$\left[\frac{\sum_{i=1}^{NI}\left(\sum_{k=1}^{NK} Y_{ijk}\right)}{NI \times NK}\right] \quad \text{for } j = 2 \text{ and } j = 3$$

For a particular test temperature the mean coded property values for the respective mixes are compared using Tukey's method of multiple comparisons.(77; 81) The test determines whether the mean coded property value which occured for a particular mix is either greater than, less than, or equal to the mean coded value which occurred for another mix. The method may also be used to determine whether the mean coded value which occurred for a number of mixes is greater than, less than or equal to the mean coded value which occurred for an equal number of other mixes.

CHAPTER 2 : ANALYSIS OF PROPERTY CHANGES : THE THREE MORTAR MIXES (CONCRETE MIXES) SUBJECTED TO TESTS AT VARIOUS TIMES DURING THE HEATING PERIOD

An analysis of variance is performed on the property changes (the coded values of a particular property) which occurred for test specimens made from the three mortar mixes and subjected to tests at various times during the heating period. For a particular property determined on test specimens at a particular test temperature, the null hypotheses are that;

(i) the coded property values do not differ significantly between mortar specimens tested at test times T hrs, T + 12 hours, T + 24 hours and T + 36 hours respectively, and

(ii) the coded property values are not significantly different for test specimens made from the three mortar mixes.

In this analysis the "A treatment" (referring to Table IV.1 in CHAPTER 1) are the various test times at which property changes were determined, viz. four test times, and the "B treatments" are the various mixes, viz. the three mortar mixes. The replications of tests are;

(i) one replication for residual linear deformation and water loss,

(ii) two replications for the coded values of compressive strength,

(iii) three replications for the coded values of ultrasonic pulse velocity, dynamic Young's modulus and Poisson's ratio.

The null hypotheses are accepted if the variance ratio, F_0, is such that

$$F_0 < F_{0,95}$$

where $F_{0,95} = F_{\emptyset_1;\, \emptyset_2}\,(0,05)$

($\emptyset_1$ and $\emptyset_2$ are the degrees of freedom used in the calculation of F_0 and in determining $F_{0,95}$ from tabled values of Fisher's F distribution)

The computed values of the variance ratio, F_0, are shown in Table IV.2. The values of $F_{0,95}$ are:

(i) For the residual linear deformation and water loss;
$F_{0,95} = F_{3;\ 6}\ (0,05) = 4,76$ for the time effect, and
$F_{0,95} = F_{2,\ 6}\ (0,05) = 5,14$ for the mix effect.

(ii) For the coded values of compressive strength;
$F_{0,95} = F_{3;\ 12}\ (0,05) = 3,49$ for the time effect, and
$F_{0,95} = F_{2;\ 12}\ (0,05) = 3,89$ for the mix effect.

(iii) For the coded values of ultrasonic velocity, dynamic Young's modulus and Poisson's ratio;
$F_{0,95} = F_{3;\ 24}\ (0,05) = 3,01$ for the time effect, and
$F_{0,95} = F_{2;\ 24}\ (0,05) = 3,40$ for the mix effect.

Comparing the respective values of $F_{0,95}$ to the values of F_0 shown in Table IV.2, the results illustrated in Table IV.3 are obtained. Table IV.3 shows the various cases for which the respective null hypotheses regarding the "mix effect" and the "time effect" were rejected, i.e. Table IV.3 shows;

(i) the instances where the coded property values of the mortar specimens tested at T hrs, T + 12 hours, T + 24 hours and T + 36 hours, respectively, are significantly different between these test times, and

(ii) the instances where the coded property values of test specimens made from the various mortar mixes are significantly different between mixes.

An exactly similar analysis was performed on the coded property values of test specimens made from the three concrete mixes and subjected to tests at T hours, T + 12 hours, T + 24 hours and T + 36 hours respectively, during the heating period. The values of F_0 from this analysis are tabulated in Table IV.4 and the values of $F_{0,95}$ are similar to those used in the analysis of the three mortar mixes. Table IV.5 shows the various cases for which the respective null hypotheses were rejected.

PROPERTY	TEST CASE	70° SAT		100° SAT		70° DRY		100° DRY		150°		250°		400°	
		Mix Effect	Time Effect	Mix Effect	Time Effect	Mix Effect	Time Effect	Mix Effect	Time Effect	Mix Effect	Time Effect	Mix Effect	Time Effect	Mix Effect	Time Effect
RESIDUAL LINEAR DEFORMATION	COLD	28,00	18,43	30,69	22,06	4,55	11,62	2,75	45,15	7,67	55,78	15,10	14,17	0,62	6,55
	WET	21,00	9,58	62,83	11,29	65,27	0,93	0,89	131,27	21,00	0,99	168,67	0,19	6,10	7,22
COMPRESSIVE STRENGTH	HOT	12,42	3,04	1,54	3,62	4,35	3,82	2,46	20,27	0,87	4,03	2,94	1,02	0,75	3,06
	COLD	1,91	1,87	1,06	5,97	0,04	5,91	14,38	19,69	24,62	7,21	1,47	1,88	9,43	4,31
	WET	26,21	15,39	9,21	3,84	1,86	1,43	1,37	14,69	10,59	9,17	31,36	8,62	13,48	3,06
WATER LOSS	COLD					7,63	50,20	5,15	296,37	0,41	7,19	12,66	3,98	12,58	7,07
	WET					4,26	0,85	4,48	6,23	4,71	1,29	11,15	1,17	12,44	2,96
PULSE VELOCITY	COLD	4,23	8,24	6,12	6,64	2,39	8,54	2,86	17,46	2,71	5,22	4,16	5,27	6,28	14,06
	WET	0,97	6,94	29,57	14,48	6,55	2,43	19,14	51,23	14,72	6,37	38,01	3,02	13,57	6,38
DYNAMIC YOUNG'S MODULUS	COLD	12,84	3,93	40,60	6,35	16,19	3,15	0,96	18,06	6,37	4,94	6,17	3,40	14,45	12,45
	WET	0,89	8,43	68,16	24,03	129,33	3,69	2,96	32,35	28,47	8,13	0,62	2,69	127,43	6,74
POISSON'S RATIO	COLD	3,31	5,02	14,39	0,73	12,08	4,19	19,62	4,09	7,68	10,85	16,30	3,99	11,78	6,58
	WET	2,64	0,09	72,38	8,91	521,72	2,81	19,83	1,94	18,19	2,77	14,55	2,15	88,96	1,39

TABLE IV.2: Computed values of the variance ratio (F_o) for the coded property values of mortar test specimens.

PROPERTY	TEST CASE	70° SAT		100° SAT		70° DRY		100° DRY		150°		250°		400°	
		Mix Effect	Time Effect	Mix Effect	Time Effect	Mix Effect	Time Effect	Mix Effect	Time Effect	Mix Effect	Time Effect	Mix Effect	Time Effect	Mix Effect	Time Effect
RESIDUAL LINEAR DEFORMATION	COLD	*	+ * ↑	*	+ * ↑		− * ↓		− * ↓	*	− * ↓	*	− * ↓		+ * ↑
	WET	*	+ * ↑	*	+ * ↑	*			− * ↓	*		*		*	*
COMPRESSIVE STRENGTH	HOT	*			− * ↑	*	− * ↑		− * ↑		− * ↑				
	COLD				− * ↑		+ * ↑	*	− * ↑	*	− * ↑			*	− * ↓
	WET	*	*	*	− * ↑				− * ↓	*	− * ↓	*	*	*	
WATER LOSS	COLD					*	+ * ↑	*	+ * ↑		+ * ↑	*		*	+ * ↑
	WET								+ * ↑			*		*	
PULSE VELOCITY	COLD	*	− * ↓	*	− * ↓		− * ↓		− * ↓		− * ↓	*	− * ↓	*	− * ↓
	WET		− * ↓	*	− * ↓	*		*	− * ↓	*	− * ↓	*	− * ↑	*	− * ↑
DYNAMIC YOUNG'S MODULUS	COLD	*	− * ↓	*	− * ↓	*	− * ↓		− * ↓	*	− * ↓	*	* ↓	*	− * ↓
	WET		− * ↓	*	− * ↓	*	− * ↓		− * ↓	*	− * ↓			*	− * ↑
POISSON'S RATIO	COLD		*	*		*	− ↓	*	− * ↓	*	− * ↓	*	− * ↑	*	− * ↑
	WET			*	*	*		*		*		*		*	

* Indicates that the null hypothesis (H_o) is rejected. ($p[H_o] < 0,05$) ie. * Indicates that the effect is significant.

TABLE IV.3: The significance of the "time effect" and the "mix effect" for the coded property values of the mortar test specimens.

PROPERTY	TEST CASE	70° SAT		100° SAT		70° DRY		100° DRY		150°		250°		400°	
		Mix Effect	Time Effect	Mix Effect	Time Effect	Mix Effect	Time Effect	Mix Effect	Time Effect	Mix Effect	Time Effect	Mix Effect	Time Effect	Mix Effect	Time Effect
RESIDUAL LINEAR DEFORMATION	COLD	15,14	7,14	22,88	6,63	3,06	7,79	1,73	29,02	8,29	20,80	10,49	4,84	12,86	9,48
	WET	2,84	3,37	37,5	17,13	9,55	1,37	0,94	15,90	16,40	0,88	0,80	1,14	5,33	7,47
COMPRESSIVE STRENGTH	HOT	1,43	1,65	6,80	14,11	3,93	4,15	6,73	17,34	2,15	3,63	10,23	1,12	3,61	2,23
	COLD	2,31	3,67	8,86	3,69	3,51	5,41	27,48	21,85	1,30	6,85	37,13	1,17	9,10	3,09
	WET	1,82	2,61	2,02	3,00	1,34	2,22	19,97	3,91	8,24	7,91	69,19	2,62	32,14	6,26
WATER LOSS	COLD					18,02	18,83	5,16	45,18	2,50	5,75	5,94	0,73	0,44	3,15
	WET					2,95	7,28	7,30	1,51	1,32	2,43	8,33	0,06	1,40	6,68
PULSE VELOCITY	COLD	4,01	6,24	1,14	3,17	10,13	4,39	2,82	6,52	2,91	7,07	7,51	2,14	4,18	14,63
	WET	14,64	0,59	9,24	3,83	17,00	0,80	2,41	4,98	8,11	10,04	0,09	13,47	0,74	1,01
DYNAMIC YOUNG'S MODULUS	COLD	1,36	4,41	4,78	7,59	84,13	3,47	51,58	2,99	1,12	5,35	35,43	4,16	6,62	10,90
	WET	2,07	4,45	2,29	12,47	109,49	4,55	57,82	17,42	3,22	16,15	2,79	59,04	2,42	4,19
POISSON'S RATIO	COLD	1,91	1,07	1,81	1,64	5,28	3,04	35,85	4,17	2,09	6,73	56,39	1,08	17,81	3,74
	WET	21,24	1,27	29,37	1,98	31,32	2,48	27,30	2,70	9,79	0,24	161,59	0,94	29,16	1,56

TABLE IV.4: Computed values of the variance ratio (F_o) for the coded property values of concrete test specimens.

PROPERTY	TEST CASE	70° SAT		100° SAT		70° DRY		100° DRY		150°		250°		400°	
		Mix Effect	Time Effect	Mix Effect	Time Effect	Mix Effect	Time Effect	Mix Effect	Time Effect	Mix Effect	Time Effect	Mix Effect	Time Effect	Mix Effect	Time Effect
RESIDUAL LINEAR DEFORMATION	COLD	*	+ * ↑	*	+ * ↑		− * ↓		− * ↓	*	− * ↓	*		*	+ * ↑
	WET			*	+ * ↑	*			− * ↓	*				*	*
COMPRESSIVE STRENGTH	HOT			*	− * ↑	*	− * ↑	*	− * ↑		− * ↑	*			
	COLD		*	*	− * ↑		*	*	− * ↑		*	*		*	− * ↓
	WET							*	− * ↓	*	− * ↓	*		*	
WATER LOSS	COLD					*	+ * ↑	*	+ * ↑		+ * ↑	*			
	WET						*	*				*			*
PULSE VELOCITY	COLD	*	− * ↓		− * ↓	*	− * ↓		− * ↓		− * ↓	*		*	− * ↓
	WET	*		*	− * ↓	*			− * ↓	*	− * ↓		− * ↑		
DYNAMIC YOUNG'S MODULUS	COLD		− * ↓	*	− * ↓	*	− * ↓	*	− * ↓		− * ↓	*	− * ↓	*	− * ↓
	WET		− * ↓		− * ↓	*	− * ↓	*	− * ↓	*	− * ↓	*	− * ↑	*	− * ↑
POISSON'S RATIO	COLD					*	*	*	− * ↓		− * ↓	*		*	+ * ↑
	WET	*		*		*		*		*		*		*	

* Indicates that the null hypothesis (H_o) is rejected. ($p[H_o] < 0{,}05$) ie. * Indicates that the effect is significant.

TABLE IV.5: The significance of the "time effect" and the "mix effect" for the coded property values of the concrete test specimens

PROPERTY	TEST CASE	70° SAT		100° SAT		70° DRY		100° DRY		150°		250°		400°	
		Mix Effect	Time Effect	Mix Effect	Time Effect	Mix Effect	Time Effect	Mix Effect	Time Effect	Mix Effect	Time Effect	Mix Effect	Time Effect	Mix Effect	Time Effect
RESIDUAL LINEAR DEFORMATION	COLD	9,00	1,00	55,3	0,10	6,94	33,93	283,00	925,00	10,49	0,71	2,62	1,99	0,34	6,08
	WET	19,18	2,82	553,00	13,00	15,39	1,64	7,09	0,86	55,60	0,63	83,90	0,00	5,66	6,02
COMPRESSIVE STRENGTH	HOT	7,48	1,89	3,93	7,48	1,34	5,79	6,71	4,98	0,79	14,30	3,39	1,53	1,46	1,05
	COLD	1,25	1,79	8,86	6,19	4,97	0,89	2,17	13,02	2,60	6,48	13,97	1,31	6,63	2,81
	WET	7,01	3,42	3,71	4,33	0,91	7,90	0,69	10,74	4,18	1,32	34,13	2,91	1,53	1,84
WATER LOSS	COLD					24,02	6,59	2,03	7,79	11,06	4,78	14,41	0,57	1,58	1,46
	WET					14,43	0,88	55,77	3,13	36,78	2,75	42,65	0,60	10,52	17,89
PULSE VELOCITY	COLD	1,79	7,84	13,71	2,69	18,12	1,53	1,62	0,92	4,97	5,23	1,66	14,98	3,90	6,79
	WET	33,78	3,36	57,15	1,49	7,63	0,97	12,61	1,60	3,84	2,01	164,71	3,15	48,21	9,42
DYNAMIC YOUNG'S MODULUS	COLD	6,81	0,91	21,63	2,64	3,71	0,17	4,22	0,85	84,32	1,43	46,08	17,35	2,82	2,71
	WET	0,80	1,53	890,54	74,13	56,38	1,86	3,81	3,22	21,88	1,49	6,77	2,01	31,11	6,08
POISSON'S RATIO	COLD	81,00	5,57	61,27	0,91	37,71	1,29	21,56	2,95	9,74	2,89	1,91	4,74	3,23	3,10
	WET	14,16	0,64	0,79	1,93	141,73	0,98	15,06	0,09	5,51	1,84	71,43	7,07	15,87	2,94

TABLE IV.6: Computed values of the variance ratio (F_o) for the coded property values of mortar test specimens during temperature cycling.

PROPERTY	TEST CASE	70° SAT		100° SAT		70° DRY		100° DRY		150°		250°		400°	
		Mix Effect	Time Effect	Mix Effect	Time Effect	Mix Effect	Time Effect	Mix Effect	Time Effect	Mix Effect	Time Effect	Mix Effect	Time Effect	Mix Effect	Time Effect
RESIDUAL LINEAR DEFORMATION	COLD	4,75	0,00	12,40	0,00	3,32	0,40	7,26	1,09	0,80	0,51	8,63	8,97	0,21	12,47
	WET	12,08	1,23	6,32	1,00	1,72	0,84	2,25	0,95	10,41	3,38	7,52	20,07	4,08	12,54
COMPRESSIVE STRENGTH	HOT	0,97	1,34	2,83	1,47	1,39	7,68	1,63	4,28	8,43	32,47	40,63	7,32	11,71	4,91
	COLD	1,57	0,99	5,26	4,69	6,37	11,36	32,74	5,93	1,43	10,89	5,26	1,52	14,73	9,24
	WET	2,74	1,02	1,59	5,14	1,14	0,96	3,75	6,14	18,91	2,69	40,49	3,81	1,04	19,59
WATER LOSS	COLD					20,17	2,22	26,61	1,29	4,81	0,53	6,98	3,98	3,20	2,34
	WET					4,99	1,23	11,21	0,12	0,97	1,26	20,89	1,10	3,25	8,78
PULSE VELOCITY	COLD	4,91	24,72	0,78	0,06	44,23	0,09	12,47	1,08	51,39	14,16	1,80	5,02	5,85	1,81
	WET	1,49	1,76	2,95	5,77	7,26	2,52	14,37	39,74	1,49	3,16	2,38	1,03	0,62	5,63
DYNAMIC YOUNG'S MODULUS	COLD	1,09	1,42	2,29	3,37	64,90	1,23	154,62	3,88	2,22	4,56	13,71	1,47	1,81	14,63
	WET	18,59	1,23	7,65	5,96	580,74	27,43	27,53	2,41	3,62	1,62	84,38	14,19	29,42	2,71
POISSON'S RATIO	COLD	1,03	1,91	3,85	2,67	21,61	1,99	54,23	1,64	3,91	1,86	14,23	1,74	2,49	5,71
	WET	28,91	1,49	19,09	0,04	51,63	1,27	29,25	0,94	3,57	0,07	54,61	1,40	51,27	3,89

TABLE IV.8: Computed values of the variance ratio (F_0) for the coded property values of concrete test specimens during temperature cycling.

(iii) For the coded values of ultrasonic pulse velocity, dynamic Young's modulus and Poisson's ratio;

$F_{0,95} = F_{2;\ 18}\ (0,05) = 3,55$ for the time effect, and

$F_{0.95} = F_{2;\ 18}\ (0,05) = 3,55$ for the mix effect.

Comparing the respective values of $F_{0,95}$ to the values of F_0 shown in Table IV.6 and Table IV.8, the results illustrated in Table IV.7 and Table IV.9 respectively, are obtained. Table IV.7 shows the various cases for which the null hypotheses regarding the "time effect" and the "mix effect" are rejected for test specimens made from the mortar mixes and Table IV.8 the various cases for which the null hypotheses are rejected for test specimens made from the concrete mixes.

2.1 Property Changes which Occurred at the Respective Time T hours, T + 12 Hours, T + 24 Hours and T + 36 Hours

It is apparent from Table IV.3 and Table IV.5 that the coded property values at test time T hours, T + 12 hours, T + 24 hours and T + 36 hours, respectively, are in many cases significantly different. In all instances where the property changes are significantly different between test times it was ascertained whether the property tends to either increase or decrease between successive test times. This was done by calculating the mean coded value which occurred at the respective test times for specimens made from the three mortar mixes (concrete mixes), ie. the value of

$$\left[\frac{\sum_{j=1}^{NJ}\left(\sum_{k=1}^{NK} Y_{ijk}\right)}{NJ \times NK}\right]$$

where NI = 4 (the number of test times)

NJ = 3 (the three mortar mixes)

NK = the number of replications as given in section 2.2.

was calculated for i = 1; 2; 3 and 4 respectively. These mean coded values are tabulated in APPENDIX V.1, Table A.V.1.1. to Table A.V.1.7. The trend exhibited by the mean coded values between successive test times was determined by performing a linear regression analysis of the mean coded values against time. In the analysis the regression coefficient (m) and the standard error of the regression coefficient (m') is calculated. The trend indicated by the

PROPERTY	TEST CASE	70° SAT		100° SAT		70° DRY		100° DRY		150°		250°		400°	
		Mix Effect	Time Effect	Mix Effect	Time Effect	Mix Effect	Time Effect	Mix Effect	Time Effect	Mix Effect	Time Effect	Mix Effect	Time Effect	Mix Effect	Time Effect
RESIDUAL LINEAR DEFORMATION	COLD	*		*		*	- * ↓	*	- * ↓	*					
	WET	*		*	+ * ↑	*		*		*		*			
COMPRESSIVE STRENGTH	HOT	*			- * ↑		- * ↑	*	- * ↑		- * ↑				
	COLD			*	- * ↑	*			+ * ↑		- * ↑	*		*	
	WET	*			- * ↑		*		*			*			
WATER LOSS	COLD					*	+ * ↑		+ * ↑	*		*			
	WET					*		*		*		*		*	*
PULSE VELOCITY	COLD		- * ↓	*		*				*	- * ↓		*	*	*
	WET	*		*		*		*		*		*		*	*
DYNAMIC YOUNG'S MODULUS	COLD	*		*		*		*		*		*	*		
	WET			*	*	*		*		*		*		*	- * ↓
POISSON'S RATIO	COLD	*	+ * ↓	*		*		*		*			*		+ * ↓
	WET	*				*		*		*		*	*	*	

* Indicates that the null hypothesis (H_o) is rejected. ($p[H_o] < 0,05$) ie. * Indicates that the effect is significant.

TABLE IV.7: The significance of the "time effect" and the "mix effect" for the coded property values of mortar test specimens during temperature cycling.

PROPERTY	TEST CASE	70° SAT		100° SAT		70° DRY		100° DRY		150°		250°		400°	
		Mix Effect	Time Effect	Mix Effect	Time Effect	Mix Effect	Time Effect	Mix Effect	Time Effect	Mix Effect	Time Effect	Mix Effect	Time Effect	Mix Effect	Time Effect
RESIDUAL LINEAR DEFORMATION	COLD			*				*				*	*		*
	WET	*		*						*		*	*		*
COMPRESSIVE STRENGTH	HOT						- * ↑		*	*	+ * ↑	*	+ * ↑	*	*
	COLD			*	- * ↑	*	*	*	*		+ * ↑	*		*	- * ↑
	WET				*				- * ↓	*	- * ↑	*			*
WATER LOSS	COLD					*		*				*			
	WET							*				*			*
PULSE VELOCITY	COLD	*	*			*		*		*	*		*	*	
	WET				- * ↑	*		*	- * ↓						*
DYNAMIC YOUNG'S MODULUS	COLD					*		*	- * ↓		*	*			- * ↑
	WET	*		*	- * ↑	*	- * ↑	*		*		*	- * ↓	*	
POISSON'S RATIO	COLD			*		*		*		*		*			+ * ↓
	WET	*		*		*		*		*		*		*	+ * ↑

* Indicates that the null hypothesis is rejected. ($p[H_o] < 0,05$) ie. * Indicates that the effect is significant.

TABLE IV.9: The significance of the "time effect" and the "mix effect" for the coded property values of the concrete test specimens during temperature cycling.

slope of the line of best fit through the mean coded values is accepted if

$$|m| > m_1$$

i.e. if the trend indicated by the worst possible line through the mean coded values is similar to the trend indicated by the line of best fit, the trend is accepted as significant.

In all instances where a significant trend was found, the trend is indicated by an arrow in Table IV.3 and Table IV.5, viz: an arrow shown thus; ↑, indicates that the particular property increases between successive test times, and an arrow shown thus; ↓, indicates that the particular property decreases between successive test times. Table IV.3 and Table IV.5 also indicate whether the coded property value that was determined from tests performed immediately that the test temperature was attained (at time T), was positive or negative, i.e. whether the particular property exhibits an increase or a reduction at time T. This is denoted by a +ve or a -ve sign. Consequently an arrangement shown as:

+ * ↑ indicates that the particular property exhibits an increase for the tests performed at time T, and a further increase occurs during the heating period.

- * ↑ indicates that the particular property is reduced for tests performed at time T, but the property increases for subsequent tests during the heating period.

2.1.1 Mortar test specimens

It is apparent from Table IV.3 that for mortar test specimens which remained fully saturated during the heating period and were tested at the respective test times (T hours, T + 12 hours, T + 24 hours and T + 36 hours):

(i) A residual linear expansion occurs for specimens tested at time T at temperatures of both 70°C and 100°C; the residual expansion increases for specimens tested at successive times during the heating period. This is apparent for test specimens which were tested immediately after cooling as well as for test specimens which were tested after cooling and 7 days in water.

(ii) The compressive strength of mortar test specimens is initially reduced (i.e. at time T) for specimens heated to 100°C but increases during the heating period. The increase in compressive strength during the heating period is apparent for test specimens tested whilst hot, for specimens tested after cooling, and for specimens tested after 7 days in water. No similar behaviour occurs for mortar specimens heated to 70°C.

(iii) Both the dynamic Young's modulus and the ultrasonic pulse velocity of mortar test specimens is reduced for specimens heated to either 70°C or 100°C and tested at time T. The reductions in these properties become greater for specimens tested at the successive test times during the heating period. These trends are apparent for test specimens which were tested immediately after cooling as well as for test specimens which were re-immersed in water for 7 days and then tested.

(iv) The coded values of Poisson's ratio for mortar specimens are significantly different between tests performed at the respective test times for specimens tested immediately after cooling from 70°C and for specimens which were soaked in water for 7 days after cooling from 100°C. However, in both the abovementioned cases there is no trend to the changes which occurred, i.e. the coded values of Poisson's ratio are significantly different between certain of the test times but it appears that these differences are due to random variations.

The property changes exhibited by mortar test specimens which underwent drying during the heating period and were tested at the respective test times (T hours, T + 12 hours, T + 24 hours and T + 36 hours) are significantly different in a number of instances. From Table IV.3 two general categories are immediately apparent, viz. the property changes which occurred for test specimens which underwent drying at either 70°C, 100°C or 150°C, and the property changes that occurred for test specimens which underwent drying at either 250°C or 400°C. For mortar test specimens which underwent drying at either 70°C, 100°C or 150°C the data in Table IV.3 indicate that:

(i) The compressive strength of specimens heated to either 70°C, 100°C or 150°C and tested whilst hot is always reduced for tests performed at time T. However, the compressive strength increases (with respect to the value at time T) for mortar specimens tested at the successive test times during the heating period when the test temperature remained constant at either 70°C, 100°C or 150°C. This behaviour is similar

to that which occurred for saturated specimens heated to 100°C and tested whilst hot; before testing is reduced for tests performed [illegible] and decrease for successive tests during the heating

(ii) The mortar specimens which were tested after cooling from either 70°C, 100°C or 150°C all exhibit the same trend with regard to the changes of the various properties between successive tests during the heating period, viz. which were tested either whilst hot or [illegible] only after cooling from 100°C. Mortar test specimens

(a) the residual linear contraction increases between tests performed also at the successive test times during the heating period, tested [illegible] at the successive times during the heating period.

(b) the water loss increases between successive tests at the various test times, in this trend is exactly opposite to the trend exhibited by specimens tested either whilst hot or after cooling from [illegible]

(c) the compressive strength increases between tests performed at the successive test times, i.e. the compressive strength increases with respect to the compressive strength at time [illegible]

(d) the dynamic Young's modulus, ultrasonic pulse velocity and the value of Poisson's ratio are always reduced when tested at time for T and the reductions in these properties become greater for tests performed at successive test times during the heating period.

(iii) Mortar test specimens which were cooled from either 70°C, 100°C or [illegible] 150°C and immersed in water for 7 days before testing, do not all heating indicate the same trends with regard to the property changes which drying occurred at the successive test times during the heating period. For mortar specimens cooled from 70°C and immersed in water for 7 days before testing, the only property which changes significantly between the respective test times is the dynamic Young's modulus; the reduction in dynamic Young's modulus becomes greater for specimens tested at successive test times during the heating period. Mortar test specimens which were cooled from 100°C and soaked in water for 7 days before testing exhibited for specimens tested at time T at either [illegible] 400°C, but tends to increase during the heating period. Specimens

(a) an increase in the residual linear contraction and water loss between successive tests during the heating period, and [illegible] residual linear deformation of mortar test specimens heated to [illegible]

(b) a reduction in dynamic Young's modulus and ultrasonic pulse respective test temperature is widely different. Mortar [illegible] velocity between tests performed at the various times during the cooled from 200°C exhibit a residual contraction which increases heating period.

successive tests during the heating period whereas mortar [illegible] cooled from 400°C exhibit a residual expansion which increases

The compressive strength of specimens cooled from 100°C and immersed [illegible] tests during the heating period. Furthermore, the [illegible]

never exhibit trends which are not apparent for the mortar specimens.

The coded property values of concrete test specimens that underwent drying at either 250°C or 400°C are significantly different between successive test times in fewer instances than for mortar specimens heated to either 250°C or 400°C. However, the trends exhibited by the property changes between test times (wherever these are significant) are identical to the trends which occurred for the corresponding property changes of mortar test specimens. Furthermore, it is apparent that there is a marked difference between the property behaviour of concrete specimens at temperatures of either 250°C or 400°C and the property behaviour of concrete specimens at lower temperature levels. This was found also for the property behaviour of mortar test specimens.

2.2 Property Changes which Occurred at Test Time T + 36 Hours, T + 36 Hours + 1 Cycle and T + 36 Hours + 2 Cycles

The property changes which occurred for test specimens made from the various concrete mixes (mortar mixes) and tested during the heating period at T + 36 hours, T + 36 hours + 1 cycle and T + 36 hours + 2 cycles, respectively, give an indication of the effect of temperature cycling on the property behaviour. Table IV.7 illustrates the cases where the coded property values of mortar test specimens are significantly different between the abovementioned test times. In Table IV.9 the significant cases for the coded property values of test specimens made from the concrete mixes are shown.

From Table IV.7 it is apparent that the coded property values of test specimens made from the various mortar mixes and subjected to temperature cycling are significantly different between successive temperature cycles in very few instances. This is apparent also for the results shown in Table IV.9 for concrete test specimens. In most instances where the coded property values are significantly different and exhibit a trend, i.e. a trend either toward further property reduction or toward an increase of the particular property for tests performed at successive temperature cycles, the trend is usually similar to that exhibited during the heating period prior to the temperature cycling. However, in some cases coded property values for tests performed at successive temperature cycles indicate a trend opposite to that exhibited by the coded property values of specimens tested during the heating period prior to temperature cycling, e.g. the dynamic Young's modulus and ultrasonic pulse velocity of saturated concrete test specimens cooled from 100°C and re-immersed in water for 7 days before testing. Furthermore, in many instances the coded property values are

significantly different between successive tests but it is not possible to determine any particular trend with regard to the property changes which occurred. This is particularly apparent for test specimens heated to temperatures of either 250°C or 400°C. The reason for not being able to determine a trend is the fact that a definite trend cannot be obtained from three data points unless the three points fall approximately on a straight line. Consequently, the method * used for determining the trend exhibited by the mean coded property values ** between the temperature cycles, usually indicates that the mean coded values exhibit no trend.

It does appear that the method of testing whether the mean coded values exhibit a trend between successive temperature cycles is too severe. However, it is thought that the chosen method would have shown the trends if the various properties had been affected to a sufficiently large extent by the temperature cycles, e.g. if temperature cycling caused a definite progressive deterioration of compressive strength, this would have become apparent. In the absence of any such trends it is concluded that the property changes which were determined from tests performed during temperature cycling do not differ appreciably from the property changes which occurred during the heating period prior to temparature cycling. However, it must be emphasised that a different conclusion may have resulted if the number of temperature cycles was greater.

2.3 Comparisons Between the Mean Coded Property Values of the Various Corcrete Mixes (Mortar Mixes)

In the analysis of variance reported in section 2.1 Table IV.3 and IV.5 the null hypotheses regarding the "mix effect" is rejected in many instances, i.e. the coded property values of the various concrete mixes (mortar mixes) are significantly different. Using Tukey's method of multiple comparisons it is possible to determine whether the property change exhibited by a particular concrete (mortar) mix is either less than, greater than or equal to the property change which occurred for any one of the other concrete mixes (mortar mixes). This is done by comparing the mean coded property values of the respective concrete mixes (mortar mixes). The mean coded value is calculated from the

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* The method used is similar to that explained previously

** The mean coded property values at T + 36 hours, T + 36 hours + 1 cycle and T + 36 hours + 2 cycles, respectively, are given in APPENDIX V.1, Table A.V.1.1 to Table A.V.1.7.

coded values at test times T hours, T + 12 hours, T + 24 hours and T + 36 hours, i.e. the value of

$$\frac{\left[\sum_{i=1}^{NI}\left(\sum_{k=1}^{NK} Y_{ijk}\right)\right]}{NI \times NK}$$

is calculated for j = 1, 2 and 3 respectively; where j = 1, j = 2 and j = 3 are used to represent the three concrete mixes (mortar mixes). These mean coded values are shown in APPENDIX V.2, Table A.V.2.1 to Table A.V.2.7 for the various concrete and mortar mixes. In Table A.V.2.1 to Table A.V.2.7 the values C_1, C_2 and C_3 refer to the mean coded values which occurred for a particular property of the concrete mixes BCY, CCX and CCY respectively; the values M_4, M_5 and M_6 are the mean coded values which occurred for a particular property of the mortar mixes BMY, CMX and CMY respectively.

It was anticipated that by using Tukey's method of pairwise comparisons it could be determined;

(i) whether there is a significant difference between the mean coded values of test specimens made from the two concrete mixes (mortar mixes) with mix proportions which differed only in the water content, viz. the concrete mixes BCY and CCX (the mortar mixes BMY and CMX) and

(ii) whether there is a significant difference between the mean coded property values of test specimens made from the two concrete mixes (mortar mixes) with mix proportions which differed only in the volumetric concentration of aggregate, viz. the concrete mixes CCX and CCY (the mortar mixes CMX and CMY).

For both (i) and (ii) above the mean coded values of the various mixes are found significantly different in a number of instances. However, no consistent trend is apparent with regard to whether the mean coded property values of a particular mix are generally greater than the mean coded property values of another mix. It appears that at certain temperature levels both of the effects (i) and (ii) influence the property behaviour whereas at other temperature levels neither of these effects influence the results. Since the pairwise comparisons yielded no information, these results are not reported. Certain of the measured properties of the various concrete mixes (mortar mixes) are compared graphically in PART V : DISCUSSION AND CONCLUSIONS, Also given in PART V is a possible reason as to why these results fail to yield any conclusive trends.

CHAPTER 3 : ANALYSIS OF PROPERTY CHANGES : THE THREE CONCRETE MIXES COMPARED TO THE THREE MORTAR MIXES

The coded values of residual linear deformation, compressive strength, percentage water loss, ultrasonic pulse velocity and dynamic Young's modulus for the three concrete mixes are compared to the coded values of these respective properties for the three mortar mixes. In order to compare the coded property values of the three concrete mixes to the coded property values of the three mortar mixes it is necessary to perform an analysis of variance to determine whether the coded property values of the six respective mixes (i.e. the three concrete and three mortar mixes) are at all significantly different.

3.1 A Comparison between the Property Changes exhibited by the Three Concrete Mixes and the Property Changes exhibited by the Three Mortar Mixes

In the analysis of variance the null hypothesis tested is that the coded values of a particular property are not significantly different for test specimens made from the various mixes, i.e. the concrete mixes as well as the mortar mixes.

In this analysis the "A treatment" (referring to Table IV.1 in CHAPTER 1) are the various mixes, viz. six mixes and the "B treatments" * are the various test times at which tests were performed viz. four test times. The replications of each "A treatment - B treatment" combination are;

(i) one replication for water loss,

(ii) two replications for the coded values of compressive strength,

(iii) three replications for the coded values of ultrasonic pulse velocity and dynamic Young's modulus.

The null hypothesis is accepted if the variance ratio, F_0, is such that

$$F_0 < F_{0,95}$$

where $F_{0,95} = F_{\emptyset_1;\ \emptyset_2}\ (0,05)$

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* No hypothesis is tested for the "B treatments"; these values refer to the coded property values at test times T hrs, T + 12 hours, T + 24 hours and T + 36 hours, respectively.

($\emptyset_1$ and $\emptyset_2$ are the degrees of freedom used to calculate F_0 and for determining $F_{0,95}$ from the tabled values of Fisher's F distribution)

The computed values of the variance ratio, F_0, are shown in Table IV.10. The values of $F_{0,95}$ are:

(i) For water loss:
$F_{0,95} = F_{5;\ 15}\ (0,05) = 2,90$ for the mix effect.

(ii) For the coded values of compressive strength;
$F_{0,95} = F_{5;\ 24}\ (0,05) = 2,62$ for the mix effect.

(iii) For the coded values of ultrasonic pulse velocity and dynamic Young's modulus;
$F_{0,95} = F_{5;\ 48}\ (0,05) = 2,42$ for the mix effect.

Comparing the respective values of $F_{0,95}$ to the value of F_0 shown in Table IV.10 it is possible to ascertain whether the null hypothesis is accepted or rejected. Table IV.11 shows the various cases for which the null hypothesis is rejected, i.e. Table IV.11 shows whether the mix effect was significant. It is apparent that at all test temperatures the mix effect is usually significant, i.e. the coded property values exhibited by the various mixes (concrete and mortar mixes) are significantly different. Using Tukey's T method of multiple comparisons it is possible to determine whether the property changes exhibited by the various concrete mixes are less than, greater than, or equal to the property changes exhibited by the various mortar mixes. This is done by comparing the mean coded property value of the various concrete mixes to the mean coded property value of the various mortar mixes. The mean coded value for a particular mix is calculated from the coded values which occurred at test times T, T + 12 hours, T + 24 hours and T + 36 hours. These mean values are shown in APPENDIX V.2, Table A.V.2.1 to Table A.V.2.7 for the various concrete mixes as well as for the various mortar mixes. For comparing the mean coded values of the three concrete mixes (C) to the mean coded values of the three mortar mixes (M), the values of C and M are determined from:

PROPERTY	TEST CASE	70° SAT		100° SAT		70° DRY		100° DRY		150°		250°		400°	
		Mix Effect	Time Effect	Mix Effect	Time Effect	Mix Effect	Time Effect	Mix Effect	Time Effect	Mix Effect	Time Effect	Mix Effect	Time Effect	Mix Effect	Time Effect
RESIDUAL LINEAR DEFORMATION	COLD	20,61	15,62	73,63	16,12	67,15	15,88	17,23	18,40	24,96	15,44	19,35	8,61	17,69	17,47
	WET	19,66	12,04	190,2	31,09	34,68	1,65	7,86	12,82	19,60	1,85	91,21	0,41	24,80	12,05
COMPRESSIVE STRENGTH	HOT	5,19	2,62	2,50	10,14	4,27	6,43	5,05	41,26	2,51	2,85	4,75	1,59	4,21	2,81
	COLD	2,07	7,77	2,31	9,27	1,65	1,98	10,84	13,04	12,54	2,91	10,54	0,96	29,16	9,70
	WET	4,72	8,24	6,82	4,82	1,49	2,89	14,62	11,74	9,40	2,43	33,79	3,47	38,09	4,65
WATER LOSS	COLD					26,74	62,64	7,00	142,3	0,96	9,90	6,66	1,37	2,97	5,21
	WET					6,88	3,68	6,30	6,70	3,21	1,72	11,13	0,71	11,30	10,22
PULSE VELOCITY	COLD	2,01	6,13	43,69	7,94	8,63	7,85	29,11	26,72	39,07	14,97	38,23	1,92	17,06	16,51
	WET	12,84	1,91	24,37	2,64	12,60	2,31	31,09	10,36	31,52	4,58	117,21	8,52	8,81	7,24
DYNAMIC YOUNG'S MODULUS	COLD	24,07	6,51	10,61	10,21	64,68	10,50	43,87	41,96	4,88	3,79	40,54	2,37	84,74	16,22
	WET	3,16	14,68	12,74	9,40	102,18	8,47	18,45	20,09	29,13	6,01	29,28	5,42	72,85	5,13

TABLE IV.10: Calculated values of the variance ratio (F_o) for the coded property values of the concrete and mortar mixes.

PROPERTY	TEST CASE	70° SAT		100° SAT		70° DRY		100° DRY		150°		250°		400°	
		Mix Effect	Time Effect	Mix Effect	Time Effect	Mix Effect	Time Effect	Mix Effect	Time Effect	Mix Effect	Time Effect	Mix Effect	Time Effect	Mix Effect	Time Effect
RESIDUAL LINEAR DEFORMATION	COLD	*	*	*	*	*	*	*	*	*	*	*	*	*	*
	WET	*	*	*	*	*		*	*	*		*		*	*
COMPRESSIVE STRENGTH	HOT	*			*	*	*	*	*			*		*	
	COLD		*		*			*	*	*		*		*	*
	WET	*	*	*	*			*	*	*		*	*	*	*
WATER LOSS	COLD					*	*	*	*		*	*		*	*
	WET					*	*	*	*			*		*	*
PULSE VELOCITY	COLD		*	*	*	*	*	*	*	*	*	*		*	*
	WET	*		*		*		*	*	*	*	*	*	*	*
DYNAMIC YOUNG'S MODULUS	COLD	*	*	*	*	*	*	*	*	*	*	*		*	*
	WET	*	*	*	*	*	*	*	*	*	*	*	*	*	*

* Indicates that the null hypothesis (H_o) is rejected ($p\,[H_o] < 0{,}05$). ie. * Indicates that the effect is significant.

TABLE IV.11: The significance of the "mix effect" and the "time effect" for the coded property values of the concrete and mortar mixes.

to that which occurred for saturated specimens heated to 100°C and tested whilst hot.

(ii) The mortar specimens which were tested after cooling from either 70°C, 100°C or 150°C all exhibit the same trend with regard to the changes of the various properties between successive tests during the heating period, viz:

(a) the residual linear contraction increases between tests performed at the successive test times during the heating period,

(b) the water loss increases between successive tests at the various test times,

(c) the compressive strength increases between tests performed at the successive test times, i.e. the compressive strength increases with respect to the compressive strength at time T.

(d) the dynamic Young's modulus, ultrasonic pulse velocity and the value of Poisson's ratio are always reduced when tested at time T and the reductions in these properties become greater for tests performed at successive test times during the heating period.

(iii) Mortar test specimens which were cooled from either 70°C, 100°C or 150°C and immersed in water for 7 days before testing, do not all indicate the same trends with regard to the property changes which occurred at the successive test times during the heating period. For mortar specimens cooled from 70°C and immersed in water for 7 days before testing, the only property which changes significantly between the respective test times is the dynamic Young's modulus; the reduction in dynamic Young's modulus becomes greater for specimens tested at successive test times during the heating period. Mortar test specimens which were cooled from 100°C and soaked in water for 7 days before testing exhibit

(a) an increase in the residual linear contraction and water loss between successive tests during the heating period, and

(b) a reduction in dynamic Young's modulus and ultrasonic pulse velocity between tests performed at the various times during the heating period.

The compressive strength of specimens cooled from 100°C and immersed

in water for 7 days before testing is reduced for tests performed at time T and decreases for successive tests during the heating period, i.e. the reduction in compressive strength of these specimens becomes greater the longer test specimens are heated. The trend exhibited by the data is exactly the opposite to the trend exhibited by specimens which were tested either whilst hot at 100°C or immediately after cooling from 100°C. Mortar test specimens cooled from 150°C and immersed in water for 7 days before testing, also indicate a further reduction in compressive strength between tests performed at the successive times during the heating period. Again this trend is exactly opposite to the trend exhibited by specimens tested either whilst hot or after cooling from 150°C. The ultrasonic pulse velocity and dynamic Young's modulus of specimens cooled from 150°C and immersed in water for 7 days is reduced for tests performed at time T and further reductions occur for successive tests during the heating period. The residual linear contraction and water loss of mortar specimens cooled from 150°C and immersed in water for 7 days do not change significantly during the heating period.

Mortar test specimens which underwent drying at either 250°C or 400°C exhibit trends (with regard to property changes between successive tests during the heating period) which are not the same as those for specimens which underwent drying at either 70°C, 100°C or 150°C. From Table IV.3 it appears that:

(i) Mortar specimens which were tested immediately after cooling from either 250°C or 400°C exhibit a reduction in dynamic Young's modulus and ultrasonic pulse velocity for tests performed at time T. The reduction in these properties becomes greater for specimens tested at successive times during the heating period. The value of Poisson's ratio is decreased for specimens tested at time T at either 250°C or 400°C, but tends to increase during the heating period. Despite the abovementioned similarities between the property changes of mortar specimens heated to 250°C and 400°C respectively, the behaviour of the residual linear deformation of mortar test specimens heated to the respective test temperatures is widely different. Mortar specimens cooled from 250°C exhibit a residual contraction which increases with successive tests during the heating period whereas mortar specimens cooled from 400°C exhibit a residual expansion which increases with successive tests during the heating period. Furthermore, the compressive

strength of mortar specimens cooled from 400°C decreases for tests performed at successive times during the heating period whereas the compressive strength does not change significantly between successive tests for specimens cooled from 250°C.

(ii) Test specimens which were cooled from either 250°C or 400°C and immersed in water for 7 days before testing exhibit a reduction in ultrasonic pulse velocity for specimens which were removed from the furnace at time T. The reduction in pulse velocity decreases between successive tests during the heating period, i.e. the pulse velocity increases. This behaviour was found also for the dynamic Young's modulus of specimens immersed in water for 7 days after cooling from 400°C. No other trends are apparent.

2.1.2 Concrete test specimens

Table IV.5 shows the instances where the coded property values for test specimens made from the concrete mixes and tested after heating for T hours, T + 12 hours, T + 24 hours and T + 36 hours respectively, are significantly different. The trend exhibited by the respective properties between successive test times is also indicated, i.e. whether the property increases or decreases during the heating period.

It is apparent from Table IV.5 that for the concrete test specimens which remained fully saturated at either 70°C or 100°C, as well as for concrete specimens which underwent drying at either 70°C, 100°C or 150°C, and were tested at T hours, T + 12 hours, T + 24 hours and T + 36 hours respectively, the trends exhibited by the various properties are usually exactly similar to the trends exhibited by the corresponding property of the mortar test specimens (given in Table IV.3). In a few instances the property changes which occurred for test specimens made from the mortar mixes are significantly different between the test times whereas the corresponding property changes which occurred for test specimens made from the concrete mixes are not significantly different between test times. This occurred for the compressive strength and ultrasonic pulse velocity of specimens which underwent drying at 70°C and were cooled and immersed in water for 7 days before testing: the compressive strength increases and pulse velocity decreases for mortar test specimens which were tested at various times during the heating period whereas the property changes which occurred for the concrete test specimens are not significantly different between test times. Of particular interest, though, is the fact that the concrete test specimens

never exhibit trends which are not apparent for the mortar specimens.

The coded property values of concrete test specimens that underwent drying at either 250°C or 400°C are significantly different between successive test times in fewer instances than for mortar specimens heated to either 250°C or 400°C. However, the trends exhibited by the property changes between test times (wherever these are significant) are identical to the trends which occurred for the corresponding property changes of mortar test specimens. Furthermore, it is apparent that there is a marked difference between the property behaviour of concrete specimens at temperatures of either 250°C or 400°C and the property behaviour of concrete specimens at lower temperature levels. This was found also for the property behaviour of mortar test specimens.

2.2 Property Changes which Occurred at Test Time T + 36 Hours, T + 36 Hours + 1 Cycle and T + 36 Hours + 2 Cycles

The property changes which occurred for test specimens made from the various concrete mixes (mortar mixes) and tested during the heating period at T + 36 hours, T + 36 hours + 1 cycle and T + 36 hours + 2 cycles, respectively, give an indication of the effect of temperature cycling on the property behaviour. Table IV.7 illustrates the cases where the coded property values of mortar test specimens are significantly different between the abovementioned test times. In Table IV.9 the significant cases for the coded property values of test specimens made from the concrete mixes are shown.

From Table IV.7 it is apparent that the coded property values of test specimens made from the various mortar mixes and subjected to temperature cycling are significantly different between successive temperature cycles in very few instances. This is apparent also for the results shown in Table IV.9 for concrete test specimens. In most instances where the coded property values are significantly different and exhibit a trend, i.e. a trend either toward further property reduction or toward an increase of the particular property for tests performed at successive temperature cycles, the trend is usually similar to that exhibited during the heating period prior to the temperature cycling. However, in some cases coded property values for tests performed at successive temperature cycles indicate a trend opposite to that exhibited by the coded property values of specimens tested during the heating period prior to temperature cycling, e.g. the dynamic Young's modulus and ultrasonic pulse velocity of saturated concrete test specimens cooled from 100°C and re-immersed in water for 7 days before testing. Furthermore, in many instances the coded property values are

significantly different between successive tests but it is not possible to determine any particular trend with regard to the property changes which occurred. This is particularly apparent for test specimens heated to temperatures of either 250°C or 400°C. The reason for not being able to determine a trend is the fact that a definite trend cannot be obtained from three data points unless the three points fall approximately on a straight line. Consequently, the method * used for determining the trend exhibited by the mean coded property values ** between the temperature cycles, usually indicates that the mean coded values exhibit no trend.

It does appear that the method of testing whether the mean coded values exhibit a trend between successive temperature cycles is too severe. However, it is thought that the chosen method would have shown the trends if the various properties had been affected to a sufficiently large extent by the temperature cycles, e.g. if temperature cycling caused a definite progressive deterioration of compressive strength, this would have become apparent. In the absence of any such trends it is concluded that the property changes which were determined from tests performed during temperature cycling do not differ appreciably from the property changes which occurred during the heating period prior to temparature cycling. However, it must be emphasised that a different conclusion may have resulted if the number of temperature cycles was greater.

2.3 Comparisons Between the Mean Coded Property Values of the Various Corcrete Mixes (Mortar Mixes)

In the analysis of variance reported in section 2.1 Table IV.3 and IV.5 the null hypotheses regarding the "mix effect" is rejected in many instances, i.e. the coded property values of the various concrete mixes (mortar mixes) are significantly different. Using Tukey's method of multiple comparisons it is possible to determine whether the property change exhibited by a particular concrete (mortar) mix is either less than, greater than or equal to the property change which occurred for any one of the other concrete mixes (mortar mixes). This is done by comparing the mean coded property values of the respective concrete mixes (mortar mixes). The mean coded value is calculated from the

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* The method used is similar to that explained previously

** The mean coded property values at T + 36 hours, T + 36 hours + 1 cycle and T + 36 hours + 2 cycles, respectively, are given in APPENDIX V.1, Table A.V.1.1 to Table A.V.1.7.

coded values at test times T hours, T + 12 hours, T + 24 hours and T + 36 hours, i.e. the value of

$$\frac{\left[\sum_{i=1}^{NI}\left(\sum_{k=1}^{NK} Y_{ijk}\right)\right]}{NI \times NK}$$

is calculated for j = 1, 2 and 3 respectively; where j = 1, j = 2 and j = 3 are used to represent the three concrete mixes (mortar mixes). These mean coded values are shown in APPENDIX V.2, Table A.V.2.1 to Table A.V.2.7 for the various concrete and mortar mixes. In Table A.V.2.1 to Table A.V.2.7 the values C_1, C_2 and C_3 refer to the mean coded values which occurred for a particular property of the concrete mixes BCY, CCX and CCY respectively; the values M_4, M_5 and M_6 are the mean coded values which occurred for a particular property of the mortar mixes BMY, CMX and CMY respectively.

It was anticipated that by using Tukey's method of pairwise comparisons it could be determined;

(i) whether there is a significant difference between the mean coded values of test specimens made from the two concrete mixes (mortar mixes) with mix proportions which differed only in the water content, viz. the concrete mixes BCY and CCX (the mortar mixes BMY and CMX) and

(ii) whether there is a significant difference between the mean coded property values of test specimens made from the two concrete mixes (mortar mixes) with mix proportions which differed only in the volumetric concentration of aggregate, viz. the concrete mixes CCX and CCY (the mortar mixes CMX and CMY).

For both (i) and (ii) above the mean coded values of the various mixes are found significantly different in a number of instances. However, no consistent trend is apparent with regard to whether the mean coded property values of a particular mix are generally greater than the mean coded property values of another mix. It appears that at certain temperature levels both of the effects (i) and (ii) influence the property behaviour whereas at other temperature levels neither of these effects influence the results. Since the pairwise comparisons yielded no information, these results are not reported. Certain of the measured properties of the various concrete mixes (mortar mixes) are compared graphically in PART V : DISCUSSION AND CONCLUSIONS. Also given in PART V is a possible reason as to why these results fail to yield any conclusive trends.

CHAPTER 3 : ANALYSIS OF PROPERTY CHANGES : THE THREE CONCRETE MIXES COMPARED TO THE THREE MORTAR MIXES

The coded values of residual linear deformation, compressive strength, percentage water loss, ultrasonic pulse velocity and dynamic Young's modulus for the three concrete mixes are compared to the coded values of these respective properties for the three mortar mixes. In order to compare the coded property values of the three concrete mixes to the coded property values of the three mortar mixes it is necessary to perform an analysis of variance to determine whether the coded property values of the six respective mixes (i.e. the three concrete and three mortar mixes) are at all significantly different.

3.1 A Comparison between the Property Changes exhibited by the Three Concrete Mixes and the Property Changes exhibited by the Three Mortar Mixes

In the analysis of variance the null hypothesis tested is that the coded values of a particular property are not significantly different for test specimens made from the various mixes, i.e. the concrete mixes as well as the mortar mixes.

In this analysis the "A treatment" (referring to Table IV.1 in CHAPTER 1) are the various mixes, viz. six mixes and the "B treatments" * are the various test times at which tests were performed viz. four test times. The replications of each "A treatment - B treatment" combination are;

(i) one replication for water loss,

(ii) two replications for the coded values of compressive strength,

(iii) three replications for the coded values of ultrasonic pulse velocity and dynamic Young's modulus.

The null hypothesis is accepted if the variance ratio, F_0, is such that

$$F_0 < F_{0,95}$$

where $F_{0,95} = F_{\phi_1;\ \phi_2}\ (0,05)$

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* No hypothesis is tested for the "B treatments"; these values refer to the coded property values at test times T hrs, T + 12 hours, T + 24 hours and T + 36 hours, respectively.

($\emptyset_1$ and $\emptyset_2$ are the degrees of freedom used to calculate F_0 and for determining $F_{0,95}$ from the tabled values of Fisher's F distribution)

The computed values of the variance ratio, F_0, are shown in Table IV.10. The values of $F_{0,95}$ are:

(i) For water loss:
$F_{0,95} = F_{5;\ 15}\ (0,05) = 2,90$ for the mix effect.

(ii) For the coded values of compressive strength;
$F_{0,95} = F_{5;\ 24}\ (0,05) = 2,62$ for the mix effect.

(iii) For the coded values of ultrasonic pulse velocity and dynamic Young's modulus;
$F_{0,95} = F_{5;\ 48}\ (0,05) = 2,42$ for the mix effect.

Comparing the respective values of $F_{0,95}$ to the value of F_0 shown in Table IV.10 it is possible to ascertain whether the null hypothesis is accepted or rejected. Table IV.11 shows the various cases for which the null hypothesis is rejected, i.e. Table IV.11 shows whether the mix effect was significant. It is apparent that at all test temperatures the mix effect is usually significant, i.e. the coded property values exhibited by the various mixes (concrete and mortar mixes) are significantly different. Using Tukey's T method of multiple comparisons it is possible to determine whether the property changes exhibited by the various concrete mixes are less than, greater than, or equal to the property changes exhibited by the various mortar mixes. This is done by comparing the mean coded property value of the various concrete mixes to the mean coded property value of the various mortar mixes. The mean coded value for a particular mix is calculated from the coded values which occurred at test times T, T + 12 hours, T + 24 hours and T + 36 hours. These mean values are shown in APPENDIX V.2, Table A.V.2.1 to Table A.V.2.7 for the various concrete mixes as well as for the various mortar mixes. For comparing the mean coded values of the three concrete mixes (C) to the mean coded values of the three mortar mixes (M), the values of C and M are determined from:

PROPERTY	TEST CASE	70° SAT		100° SAT		70° DRY		100° DRY		150°		250°		400°	
		Mix Effect	Time Effect	Mix Effect	Time Effect	Mix Effect	Time Effect	Mix Effect	Time Effect	Mix Effect	Time Effect	Mix Effect	Time Effect	Mix Effect	Time Effect
RESIDUAL LINEAR DEFORMATION	COLD	20,61	15,62	73,63	16,12	67,15	15,88	17,23	18,40	24,96	15,44	19,35	8,61	17,69	17,47
	WET	19,66	12,04	190,2	31,09	34,68	1,65	7,86	12,82	19,60	1,85	91,21	0,41	24,80	12,05
COMPRESSIVE STRENGTH	HOT	5,19	2,62	2,50	10,14	4,27	6,43	5,05	41,26	2,51	2,85	4,75	1,59	4,21	2,81
	COLD	2,07	7,77	2,31	9,27	1,65	1,98	10,84	13,04	12,54	2,91	10,54	0,96	29,16	9,70
	WET	4,72	8,24	6,82	4,82	1,49	2,89	14,62	11,74	9,40	2,43	33,79	3,47	38,09	4,65
WATER LOSS	COLD					26,74	62,64	7,00	142,3	0,96	9,90	6,66	1,37	2,97	5,21
	WET					6,88	3,68	6,30	6,70	3,21	1,72	11,13	0,71	11,30	10,22
PULSE VELOCITY	COLD	2,01	6,13	43,69	7,94	8,63	7,85	29,11	26,72	39,07	14,97	38,23	1,92	17,06	16,51
	WET	12,84	1,91	24,37	2,64	12,60	2,31	31,09	10,36	31,52	4,58	117,21	8,52	8,81	7,24
DYNAMIC YOUNG'S MODULUS	COLD	24,07	6,51	10,61	10,21	64,68	10,50	43,87	41,96	4,88	3,79	40,54	2,37	84,74	16,22
	WET	3,16	14,68	12,74	9,40	102,18	8,47	18,45	20,09	29,13	6,01	29,28	5,42	72,85	5,13

TABLE IV.10: Calculated values of the variance ratio (F_o) for the coded property values of the concrete and mortar mixes.

PROPERTY	TEST CASE	70° SAT		100° SAT		70° DRY		100° DRY		150°		250°		400°	
		Mix Effect	Time Effect	Mix Effect	Time Effect	Mix Effect	Time Effect	Mix Effect	Time Effect	Mix Effect	Time Effect	Mix Effect	Time Effect	Mix Effect	Time Effect
RESIDUAL LINEAR DEFORMATION	COLD	*	*	*	*	*	*	*	*	*	*	*	*	*	*
	WET	*	*	*	*	*		*	*	*		*		*	*
COMPRESSIVE STRENGTH	HOT	*			*	*	*	*	*			*		*	
	COLD		*		*			*	*	*		*		*	*
	WET	*	*	*	*			*	*	*		*	*	*	*
WATER LOSS	COLD					*	*	*	*		*	*		*	*
	WET					*	*	*	*			*		*	*
PULSE VELOCITY	COLD		*	*	*	*	*	*	*	*	*	*		*	*
	WET	*		*		*		*	*	*	*	*	*	*	*
DYNAMIC-YOUNG'S MODULUS	COLD	*	*	*	*	*	*	*	*	*	*	*		*	*
	WET	*	*	*	*	*	*	*	*	*	*	*	*	*	*

* Indicates that the null hypothesis (H_o) is rejected ($p\,[H_o] < 0{,}05$). ie. * Indicates that the effect is significant.

TABLE IV.11: The significance of the "mix effect" and the "time effect" for the coded property values of the concrete and mortar mixes.

$$C = \frac{C_1 + C_2 + C_3}{3}$$

$$M = \frac{M_4 + M_5 + M_6}{3}$$

where; C_1, C_2 and C_3 are the mean coded values of a particular property at a particular temperature, for the concrete mixes BCY, CCX and CCY respectively, and

M_4, M_5 and M_6 are the mean coded values of a particular property at a particular test temperature, for the mortar mixes BMY, CMX and CMY, respectively.

The value of $|C - M|$ is compared to Tukey's coefficient calculated from:

$$q^{\alpha}_{I;\ (I-1)(J-1)} \sqrt{\frac{MSe}{J}} \qquad \text{(for one replication)}$$

$$q^{\alpha}_{I;\ IJ(K-1)} \sqrt{\frac{MSe}{JK}} \qquad \text{(for more than one replication)}$$

where : $I = 6$; I is the number of levels of "A treatments" (the total number of mixes)

$J = 4$; J is the number of levels of "B treatments" (the number of test times)

K = the number of replications of treatments

$\alpha = 0{,}05$; α is the probability of incorrectly rejecting the null hypothesis

q = the value at the α significance level of the Studentized range (for the appropriate degrees of freedom)

MSe is the error mean square

The calculated values of Tukey's coefficient are tabulated * in Table IV.12 and the results of the multiple comparisons are given in Table IV.13. The notation used in Table IV.13 is as follows:

(i) $C < M$ indicates that the property change was positive and the mean coded values of the concrete mixes are less than the mean coded values of the mortar mixes.

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* Values are only given for the cases in which the analysis of variance indicated significant differences.

PROPERTY	COEFFICIENT CALCULATED FROM	TEST CASE	CALCULATED VALUE OF TUKEY'S COEFFICIENT FOR MULTIPLE COMPARISONS						
			70° SAT	100° SAT	70° DRY	100° DRY	150°	250°	400°
RESIDUAL LINEAR DEFORMATION	$4,59\sqrt{\frac{MSe^*}{4}}$	COLD	0,038	0,032	0,046	0,130	0,152	0,104	0,500
		WET	0,038	0,019	0,045	0,077	0,058	0,222	0,664
COMPRESSIVE STRENGTH	$4,37\sqrt{\frac{MSe}{8}}$	HOT	2,80		3,16	2,82		4,70	3,76
		COLD				2,84	4,40	3,93	3,23
		WET	3,56	3,19	4,37	2,98	5,65	2,73	2,15
WATER LOSS	$4,59\sqrt{\frac{MSe}{4}}$	COLD			4,53	5,45	9,47	5,28	5,30
		WET			1,24	1,12	2,63	1,76	1,47
PULSE VELOCITY	$5,05\sqrt{\frac{MSe}{12}}$	COLD		90,0	152,0	80,0	128,0	164,0	204,0
		WET	97,0	110,0	94,0	134,0	126,0	78,0	114,0
DYNAMIC YOUNG'S MODULUS	$5,05\sqrt{\frac{MSe}{12}}$	COLD	1,06	1,47	1,57	1,70	1,80	2,30	2,57
		WET	1,23	1,44	1,72	1,44	1,58	1,53	2,21

* MSe is the mean square error.

TABLE IV.12: The calculated values of Tukey's coefficient for a comparison between the mean coded property values of the three concrete mixes and the mean coded property values of the three mortar mixes.

PROPERTY	TEST CASE	RESULTS OF COMPARISONS BETWEEN CONCRETE AND MORTAR MIXES						
		70^{o} SAT	100^{o} SAT	70^{o} DRY	100^{o} DRY	150^{o}	250^{o}	400^{o}
RESIDUAL LINEAR DEFORMATION	COLD	$C < M$	$C < M$	$\|C\| < \|M\|$	$\|C\| < \|M\|$	$\|C\| < \|M\|$	$\|C\| < \|M\|$	$C < M$
	WET	$C < M$	$C < M$	$\|C\| < \|M\|$	$\|C\| < \|M\|$	$\|C\| = \|M\|$	$C < M$	$C < M$
COMPRESSIVE STRENGTH	HOT	$\|C\| = \|M\|$	$\|C\| = \|M\|$	$\|C\| = \|M\|$	$\|C\| = \|M\|$	$C = M$	$C = M$	$\|C\| = \|M\|$
	COLD	$\|C\| = \|M\|$	$\|C\| = \|M\|$	$C = M$	$\|C\| = \|M\|$	$C > M$	$\|C\| = \|M\|$	$\|C\| < \|M\|$
	WET	$\|C\| = \|M\|$	$\|C\| = \|M\|$	$\|C\| = \|M\|$	$\|C\| = \|M\|$	$\|C\| = \|M\|$	$\|C\| = \|M\|$	$\|C\| < \|M\|$
WATER LOSS	COLD			$C = M$	$C = M$	$C = M$	$C = M$	$C = M$
	WET			$C = M$	$C = M$	$C = M$	$C = M$	$C = M$
PULSE VELOCITY	COLD	$\|C\| = \|M\|$	$\|C\| < \|M\|$	$\|C\| = \|M\|$	$\|C\| < \|M\|$	$\|C\| < \|M\|$	$\|C\| < \|M\|$	$\|C\| < \|M\|$
	WET	$\|C\| = \|M\|$	$\|C\| < \|M\|$	$\|C\| = \|M\|$	$\|C\| < \|M\|$	$\|C\| < \|M\|$	$\|C\| < \|M\|$	$\|C\| = \|M\|$
DYNAMIC YOUNG'S MODULUS	COLD	$\|C\| = \|M\|$	$\|C\| = \|M\|$	$\|C\| = \|M\|$	$\|C\| = \|M\|$	$\|C\| = \|M\|$	$\|C\| > \|M\|$	$\|C\| > \|M\|$
	WET	$\|C\| = \|M\|$	$\|C\| = \|M\|$	$\|C\| = \|M\|$	$\|C\| = \|M\|$	$\|C\| < \|M\|$	$\|C\| < \|M\|$	$\|C\| = \|M\|$

$$C = \left[\frac{C_1 + C_2 + C_3}{3}\right] \quad \text{and} \quad M = \left[\frac{M_4 + M_5 + M_6}{3}\right]$$

TABLE IV.13: The results of comparisons between the mean coded property values of the three concrete mixes and the mean coded property values of the three mortar mixes.

(ii) $|C| < |M|$ indicates that the property change was negative and that the mean coded values for the concrete mixes are greater than the mean coded values for the mortar mixes.

It is apparent from Table IV.13 that for test specimens which remained fully saturated during the heating period:

(i) The residual linear expansion exhibited by concrete test specimens heated to either 70°C or 100°C is less than the residual expansion which occurred for mortar test specimens at these temperature levels. This occurred for test specimens which were tested immediately after cooling as well as for specimens which were cooled and re-immersed in water for 7 days before testing.

(ii) The reduction in compressive strength of concrete test specimens at either 70°C or 100°C is not significantly different from the reduction in compressive strength of the mortar test specimens at these temperature levels. This is apparent for test specimens tested whilst hot, for test specimens tested after cooling and for test specimens tested after cooling and 7 days in water.

(iii) The reduction in ultrasonic pulse velocity of concrete test specimens heated to 70°C is not significantly different from the change in ultrasonic pulse velocity, which occurred for mortar test specimens heated to 70°C. However, mortar test specimens heated to 100°C exhibit greater reduction in pulse velocity than concrete test specimens heated to 100°C, both for specimens tested immediately after cooling and for test specimens which were re-immersed in water for 7 days before testing.

(iv) The dynamic Young's modulus of both concrete and mortar test specimens is always reduced at temperatures of either 70°C or 100°C. The change in dynamic Young's modulus for concrete specimens is similar to the change which occurred for mortar test specimens. This is apparent for specimens tested immediately after cooling as well as for specimens tested after cooling and 7 days in water.

It appears from the above results that the coarse aggregate did not influence the reduction of either compressive strength, ultrasonic pulse velocity or dynamic Young's modulus of concrete test specimens. The fact that the mortar test specimens exhibit greater residual expansion than concrete specimens may

be an indication that the observed property changes occurred as a result of either a chemical change within the mortar (i.e. within the cement phase) or a physical change caused by cement/fine aggregate interaction (i.e. a change caused by the difference in the thermal expansion coefficients of these constituents).

The results shown in Table IV.13 for test specimens that underwent drying indicate that:

(i) The residual linear contraction exhibited by test specimens which were tested immediately after cooling from either 70°C, 100°C, 150°C or 250°C is always less for concrete specimens than for specimens made from the mortar mixes. Test specimens which underwent drying at 400°C and were tested immediately after cooling exhibit a residual expansion; the residual expansion of test specimens made from the mortar mixes is greater than the residual expansion of test specimens made from the concrete mixes. The test specimens which were cooled from either 70°C, 100°C or 150°C and immersed in water for 7 days before testing always exhibit a residual contraction. The residual contraction of mortar test specimens cooled from either 70°C or 100°C is greater than the residual contraction of concrete specimens cooled from these temperature levels. However, for test specimens cooled from 150°C and immersed in water for 7 days the residual contraction of mortar specimens is not significantly different from the residual contraction of concrete specimens. Test specimens which were cooled from either 250°C or 400°C and immersed in water for 7 days before testing exhibit a residual expansion. This residual expansion is greater for mortar test specimens that for concrete test specimens. Consequently, it appears that the residual linear deformation of the concrete test specimens is dominated by the residual linear deformation which occurred for the mortar.

(ii) At all temperature levels, the percentage water loss of the concrete test specimens is not significantly different from the percentage water loss of the mortar test specimens. This occurred for specimens which were tested immediately after cooling and for specimens which were tested after 7 days immersion in water.

(iii) The compressive strength of test specimens heated to either 70°C, 100°C, 150°C, 250°C or 400°C, and tested either whilst hot, after

cooling or after 7 days in water is usually reduced. The reduction in compressive strength of mortar test specimens is always greater than, or equal to, the reduction in compressive strength of concrete test specimens. In some instances, the compressive strength of test specimens increases; in these cases the increase in compressive strength of the mortar test specimens was not significantly different from the increase in compressive strength of the concrete specimens.

(iv) The ultrasonic pulse velocity of heated test specimens is always lower than the pulse velocity of unheated specimens. Mortar test specimens which were tested immediately after cooling exhibit greater reductions in pulse velocity than concrete specimens. This could have occurred as a result of the greater water loss (absolute water loss, not percentage water loss) of the mortar test specimens. However, mortar test specimens which were re-immersed in water for 7 days before testing also exhibit greater reductions in pulse velocity than concrete test specimens which underwent similar treatment.

(v) The dynamic Young's modulus of test specimens which remained fully saturated at either 70°C or 100°C is always reduced. The reduction in dynamic Young's modulus for concrete test specimens is not significantly different from the reduction in dynamic Young's modulus of mortar test specimens, both for test specimens which were cooled before testing and for test specimens which were cooled and immersed in water for 7 days before testing. Concrete test specimens which underwent drying at either 70°C, 100°C or 150°C and were tested after cooling, exhibit reductions in dynamic Young's modulus which are similar to the reductions exhibited by mortar test specimens. However, concrete specimens tested after cooling from either 250°C or 400°C exhibit greater reductions in dynamic Young's modulus than mortar test specimens. The reduction in dynamic Young's modulus of concrete test specimens cooled from any of the various temperature levels and immersed in water for 7 days before testing, is never greater than the reduction in dynamic Young's modulus of mortar specimens that underwent similar treatment.

The above results do not indicate conclusively that the property reduction which occurred for the various concrete mixes is entirely due to changes which occurred within the mortar. However, the data does suggest that the presence of coarse aggregate is not necessarily detrimental to the property behaviour of concrete at elevated temperatures.

3.2 A Comparison between the Property Changes exhibited by the Three Concrete Mixes and the Property Changes exhibited by the Three Mortar Mixes during the Temperature Cycling Period

An analysis similar to that reported in section 3.1 is performed on the coded values exhibited by the concrete and mortar test specimens which were subjected to temperature cycling. For a particular property determined on test specimens at a particular temperature, the null hypothesis is that the coded values do not differ significantly for the various mixes.

The "A treatments" (referring to Table IV.1 in CHAPTER 1) are the various mixes, viz. six mixes, and the "B treatments" * are the test times viz. three test times. The replications are as given in section 3.1.

The null hypothesis is accepted if the variance ratio, F_0, is such that:

$$F_0 < F_{0,95}$$

where $F_{0,95} = F_{\emptyset_1;\ \emptyset_2}\ (0,05)$

($\emptyset_1$ and $\emptyset_2$ are the appropriate degrees of freedom used to calculate F_0 and to determine $F_{0,95}$ from tabled values of Fisher's F distribution)

The computed values of the variance ratio, F_0, are shown in Table IV.14. The values of $F_{0,95}$ are:

(i) For the water loss;
$F_{0,95} = F_{5;\ 10}\ (0,05) = 3,33$ for the mix effect.

(ii) For the coded values of compressive strength;
$F_{0,95} = F_{5;\ 18}\ (0,05) = 2,77$ for the mix effect.

(iii) For the coded values of ultrasonic pulse velocity and dynamic Young's modulus;
$F_{0,95} = F_{5;\ 36}\ (0,05) = 2,49$ for the mix effect.

Comparing the respective values of $F_{0,95}$ to the values of F_0 shown in Table IV.14, it is possible to ascertain whether the null hypothesis is

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* No hypothesis is tested for the "B treatments"; these values refer to the coded property values at T + 36 hrs, T + 36 hrs + 1 cycle and T + 36 hrs + 2 cycles, respectively.

PROPERTY	TEST CASE	70° SAT		100° SAT		70° DRY		100° DRY		150°		250°		400°	
		Mix Effect	Time Effect	Mix Effect	Time Effect	Mix Effect	Time Effect	Mix Effect	Time Effect	Mix Effect	Time Effect	Mix Effect	Time Effect	Mix Effect	Time Effect
RESIDUAL LINEAR DEFORMATION	COLD	23,74	0,85	197,7	7,04	34,64	3,18	337,8	8,00	105,9	1,44	45,65	8,79	3,48	9,17
	WET	2,85	3,62	55,99	0,53	7,98	1,55	45,07	0,04	43,08	3,24	73,90	0,66	18,84	13,31
COMPRESSIVE STRENGTH	HOT	6,41	1,55	2,64	6,64	1,43	4,36	1,06	0,72	6,16	1,99	24,43	2,74	9,16	0,97
	COLD	1,43	1,78	2,11	2,66	9,48	0,85	12,35	1,40	1,92	4,94	14,78	1,06	23,67	7,24
	WET	2,79	2,61	5,46	3,16	1,21	1,37	5,64	3,06	9,68	2,81	27,84	0,42	5,96	2,91
WATER LOSS	COLD					33,04	8,48	14,49	6,56	4,59	0,67	0,38	2,16	2,17	2,42
	WET					17,70	1,05	17,97	1,02	8,20	0,22	32,23	0,82	9,47	2,60
PULSE VELOCITY	COLD	0,57	0,63	33,25	0,91	37,34	0,09	41,15	2,71	56,25	0,09	13,07	9,78	9,84	2,96
	WET	6,28	0,63	27,43	2,76	6,78	2,02	97,18	7,40	31,43	0,27	25,41	2,33	4,03	1,32
DYNAMIC YOUNG'S MODULUS	COLD	14,36	1,04	9,34	2,39	32,20	0,74	103,29	2,47	8,17	0,58	38,25	5,53	63,91	9,87
	WET	5,13	0,62	14,64	8,44	69,60	0,59	19,46	2,13	13,22	1,79	66,59	4,87	17,45	2,72

TABLE IV.14: Calculated values of the variance ratio (F_0) for the coded property values of the concrete and mortar mixes (during temperature cycling).

accepted or rejected. Table IV.15 illustrates the various cases for which the null hypothesis is rejected, i.e. whether the coded values exhibited by the six mixes (the three concrete and three mortar mixes) are significantly different.

It is particularly noticeable from Table IV.15 that the 'mix effect' is usually significant, i.e. the coded property values of the various mixes (concrete and mortar mixes) usually differ significantly. It is possible to determine whether the property changes exhibited by the various concrete mixes are less than, greater than or equal to the property changes which occurred for the various mortar mixes. This is done by calculating the mean coded property values of each mix from the coded values at test times T + 36 hours, T + 36 hours + 1 cycle and T + 36 hours + 2 cycles. The mean coded property values of the concrete mixes is compared to the mean coded values * of the mortar mixes using Tukey's method as in section 3.1.

The calculated values of Tukey's coefficient are tabulated in Table IV.16 and the results of the comparison between the property changes which occurred for the three concrete mixes and the property changes which occurred for the three mortar mixes, are shown in Table IV.17. The notation used in Table IV.17 is similar to that in section 3.1.

It is apparent from Table IV.17 that the results of the comparisons between the property changes which occurred for the concrete mixes and the property changes which occurred for the various mortar mixes, are almost exactly identical to the comparisons reported in section 3.1. Of particular interest are the property changes which occurred for compressive strength, ultrasonic pulse velocity and dynamic Young's modulus: in almost every instance the property change which occurred for the mortar test specimens is greater than, or equal to, the property change which occurred for concrete test specimens. The exception to this was the change in dynamic Young's modulus of test specimens cooled from either 250°C or 400°C. In these two cases the concrete test specimens exhibit a greater reduction in dynamic Young's modulus than the mortar test specimens. A similar trend was found in section 3.1 for the dynamic Young's modulus of specimens tested immediately after cooling from either 250°C or 400°C.

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* The mean coded values of the three concrete mixes (mortar mixes) are given in APPENDIX V.3, Table A.V.3.1 to Table A.V.3.7.

PROPERTY	TEST CASE	70° SAT		100° SAT		70° DRY		100° DRY		150°		250°		400°	
		Mix Effect	Time Effect	Mix Effect	Time Effect	Mix Effect	Time Effect	Mix Effect	Time Effect	Mix Effect	Time Effect	Mix Effect	Time Effect	Mix Effect	Time Effect
RESIDUAL LINEAR DEFORMATION	COLD	*		*	*	*		*	*	*		*	*	*	*
	WET			*		*		*		*		*		*	*
COMPRESSIVE STRENGTH	HOT	*			*		*			*		*		*	
	COLD					*		*			*	*		*	*
	WET	*		*				*		*		*		*	
WATER LOSS	COLD					*	*	*	*	*					
	WET					*		*		*		*		*	
PULSE VELOCITY	COLD			*		*		*		*		*	*	*	
	WET	*		*		*		*	*	*		*		*	
DYNAMIC YOUNG'S MODULUS	COLD	*		*		*		*		*		*	*	*	*
	WET	*		*	*	*		*		*		*	*	*	

* Indicates the the null hypothesis (H_o) is rejected. ($p[H_o] < 0,05$) ie. * Indicates that the effect is significant.

TABLE.IV.15: The significance of the "mix effect" and the "time effect" for the coded property values of the concrete and mortar mixes during temperature cycling.

PROPERTY	COEFFICIENT CALCULATED FROM	TEST CASE	CALCULATED VALUE OF TUKEY'S COEFFICIENT FOR MULTIPLE COMPARISONS						
			70° SAT	100° SAT	70° DRY	100° DRY	150°	250°	400°
RESIDUAL LINEAR DEFORMATION	$4,91\sqrt{\frac{MSe^*}{3}}$	COLD	0,055	0,025	0,097	0,051	0,106	0,113	1,04
		WET		0,042	0,138	0,053	0,014	0,254	0,791
COMPRESSIVE STRENGTH	$4,49\sqrt{\frac{MSe}{6}}$	HOT	3,66				5,19	3,36	4,35
		COLD		2,66	4,49	3,17		3,38	4,37
		WET	3,32	3,96		5,41	5,05	3,00	5,38
WATER LOSS	$4,91\sqrt{\frac{MSe}{3}}$	COLD			4,30	4,16	4,36		
		WET			1,23	0,86	2,58	1,41	1,41
PULSE VELOCITY	$5,16\sqrt{\frac{MSe}{9}}$	COLD		118,1	102,6	74,1	99,4	243,8	231,0
		WET	91,7	100,3	166,4	85,0	146,3	59,6	233,7
DYNAMIC YOUNG'S MODULUS	$5,16\sqrt{\frac{MSe}{9}}$	COLD	1,42	1,47	2,57	1,30	1,94	2,47	2,93
		WET	1,68	1,46	2,26	1,91	2,50	1,34	1,73

* MSe is the mean square error.

TABLE IV.16: The calculated values of Tukey's coefficient for a comparison between the mean coded property values of the three concrete mixes and the mean coded property values of the three mortar mixes during temperature cycling.

PROPERTY	TEST CASE	RESULTS OF COMPARISONS BETWEEN CONCRETE AND MORTAR MIXES DURING CYCLING						
		70° SAT	100° SAT	70° DRY	100° DRY	150°	250°	400°
RESIDUAL LINEAR DEFORMATION	COLD	$C < M$	$C < M$	$\|C\| < \|M\|$	$\|C\| < \|M\|$	$\|C\| < \|M\|$	$\|C\| < \|M\|$	$C = M$
	WET	$C < M$	$C < M$	$\|C\| = \|M\|$	$\|C\| < \|M\|$	$\|C\| < \|M\|$	$C < M$	$C < M$
COMPRESSIVE STRENGTH	HOT	$\|C\| = \|M\|$	$\|C\| = \|M\|$	$\|C\| = \|M\|$	$\|C\| = \|M\|$	$C = M$	$C = M$	$\|C\| = \|M\|$
	COLD	$\|C\| = \|M\|$	$\|C\| = \|M\|$	$C = M$	$\|C\| = \|M\|$	$C = M$	$\|C\| = \|M\|$	$\|C\| < \|M\|$
	WET	$\|C\| = \|M\|$	$\|C\| = \|M\|$	$\|C\| = \|M\|$	$\|C\| = \|M\|$	$\|C\| = \|M\|$	$\|C\| = \|M\|$	$\|C\| = \|M\|$
WATER LOSS	COLD			$C > M$	$C = M$	$C = M$	$C = M$	$C = M$
	WET			$C = M$	$C = M$	$C = M$	$C = M$	$C = M$
PULSE VELOCITY	COLD	$\|C\| = \|M\|$	$C < M$	$\|C\| = \|M\|$	$\|C\| < \|M\|$	$\|C\| < \|M\|$	$\|C\| < \|M\|$	$\|C\| = \|M\|$
	WET	$\|C\| = \|M\|$	$\|C\| < \|M\|$	$\|C\| = \|M\|$	$\|C\| < \|M\|$	$\|C\| < \|M\|$	$\|C\| < \|M\|$	$\|C\| = \|M\|$
DYNAMIC YOUNG'S MODULUS	COLD	$\|C\| = \|M\|$	$\|C\| = \|M\|$	$\|C\| = \|M\|$	$\|C\| = \|M\|$	$\|C\| = \|M\|$	$\|C\| > \|M\|$	$\|C\| > \|M\|$
	WET	$\|C\| = \|M\|$	$\|C\| = \|M\|$	$\|C\| = \|M\|$	$\|C\| = \|M\|$	$\|C\| = \|M\|$	$\|C\| < \|M\|$	$\|C\| = \|M\|$

$$C = \frac{C_1 + C_2 + C_3}{3} \quad \text{and} \quad M = \frac{M_4 + M_5 + M_6}{3}$$

TABLE IV.17: The results of comparisons between the mean coded property values of the three concrete mixes and the mean coded property values of the three mortar mixes.

It appears from the results reported in sections 3.1 and 3.2 that the property behaviour of concrete test specimens

(i) which remained fully saturated at either 70°C or 100°C, and

(ii) which underwent drying at either 70°C, 100°C or 150°C,

is largely governed by the changes which occur in the mortar phase, i.e. the presence of coarse aggregate does not seem to have an adverse affect on the behaviour of the measured properties at these temperature levels. The data further suggests that for test specimens which underwent drying at either 250°C or 400°C, the coarse aggregate may in some instances affect the behaviour of certain concrete properties.

PART V

DISCUSSION AND CONCLUSIONS

Introduction

The experimental results and statistical analyses reported in PART III and PART IV respectively, indicate that:

(i) The physical properties of concrete and mortar test specimens are significantly affected if specimens are subjected to elevated temperature. The temperature level has a large influence on the properties of heated test specimens. Test specimens which remained fully saturated during heating do not exhibit the same property behaviour as test specimens which underwent drying at corresponding temperatures.

(ii) The properties of concrete and mortar test specimens may change significantly during the heating period. The changes in the physical properties which occurred for specimens which remained fully saturated during the heating period are not always the same as the changes which occurred for test specimens which underwent drying during the heating period. Furthermore, the property changes which occurred for test specimens which underwent drying at temperatures of either $70^{o}C$, $100^{o}C$ or $150^{o}C$ appear to be markedly different from the property changes exhibited by test specimens which underwent drying at either $250^{o}C$ or $400^{o}C$.

(iii) At a particular temperature level the property changes exhibited by test specimens are in many instances significantly different for the various concrete or the various mortar mixes. However, by comparing the property changes which occurred for test specimens made from

(i) the two concrete (or mortar) mixes which differed only in water content, i.e. concrete mixes BCY and CCX (mortar mixes BMY and CMX), and

(ii) the two concrete (or mortar) mixes which differed only in volumetric concentration of aggregate, i.e. concrete mixes CCX and CCY (mortar mixes CMX and CMY).

it was found * that there was no particular trend to the property changes which occurred, i.e. test specimens of a particular mix (as in either (i) or (ii) above) did not exhibit consistently better property behaviour at the various test temperatures than test specimens of another mix.

(iv) At all the test temperatures the property changes which occurred for test specimens made from the various mortar mixes are usually either greater than or equal to the property change which occurred for test specimens made from the various concrete mixes. The exception to this occurred for the dynamic Young's modulus of specimens tested after cooling from temperatures of either 250°C or 400°C. At these temperatures the dynamic Young's modulus of concrete test specimens is more reduced than the dynamic Young's modulus of mortar test specimens.

(v) Temperature cycling had no additional effect on the changes in the physical properties of either concrete or mortar test specimens at a particular temperature level. However, it is likely that this would not have been the case if test specimens had been subjected to a greater number of temperature cycles.

In CHAPTER 1 to CHAPTER 7 these aspects, with the exception of (v) above, are considered for each of the various properties determined on heated concrete and mortar test specimens. Wherever possible, the results are compared to existing data obtained by other investigators.

CHAPTER 1 : WATER LOSS OF TEST SPECIMENS DURING HEATING

The percentage water loss is calculated from the total amount of water (W_t) in test specimens prior to heating. The method of calculating W_t is given in APPENDIX 1.4. Also given in APPENDIX 1.4 is the method of calculating the respective quantities of water in the capillary pores (W_c), water in the gel pores (W_g) and the chemically combined water (W_n). The formulae used for the calculation of W_c, W_g and W_n are derived for hydration of pure cement paste specimens and not for the hydration of mortar or concrete test specimens. In mortar or concrete test specimens absorption of water by the aggregates will occur. This effectively changes the $^w/_c$ ratio. However, this will not alter the quantity of chemically combined water or the quantity of water in the gel pores,

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* The results of these comparisons are not reported.

since both of these quantities are independent of the $^{w}/_{c}$ ratio. Thus the absorption of water by aggregate only affects the amount of water in the capillary pores. In view of the fact that the water in the capillary pores and any water absorbed by the aggregate may both be classed as "free water", the water absorbed by the aggregate is considered as part of the capillary water.

The approximate percentage water loss of concrete and mortar test specimens after 40 hrs heating ranges between

28% and 37% at 70°C,
57% and 65% at 100°C,
69% and 73% at 150°C,
73% and 78% at 250°C, and
78% and 86% at 400°C.

The experimental results obtained from continuous water loss measurements on test specimens at the various temperature levels indicate that at all temperature levels the water loss increases with time during the heating period. For test specimens heated to temperatures of either 70°C or 100°C the water loss occurs gradually during the heating period. At temperatures of 150°C, 250°C and 400°C the major water loss occurs during the time period when test specimens are heated to the desired temperature level. However, at these temperatures there is a significant further water loss during the period when the test temperatures remain constant.

It is particularly interesting that the total percentage water loss of test specimens after 40 hours heating at 150°C is in good agreement with the total amount of water not chemically combined within the cement paste. This is apparent from the date for percentage water loss at 150°C shown above: the total percentage water in the gel pores and capillary pores ranged between 69,5% and 73,5% for the various mixes used in the investigation and the percentage water loss after 40 hours heating at 150°C ranged between 69% and 73% for these mixes. Consequently, it appears that at temperatures of 150°C and below, the water loss is entirely due to the removal of water from the gel pores and capillary pores. However, it should be remembered that at a temperature level of 150°C a loss of chemically combined water also occurs. The loss of chemically combined water is due to the dehydration of tobermorite gel ($C_{1,62}\ SH_{1,5}$) into β-wollastonite (β-CS) and $\beta\text{-}C_2S$[86]. Assuming that there are no intermediate dehydration products in the formation of the β-CS and $\beta\text{-}C_2S$, the dehydration of tobermorite gel with temperature may be described by the following equation[86]:

$$C_{1,62}SH_{1,5} \longrightarrow (1-R_t)\, C_{1,62}SH_{1,5} + 0,62R_t C_2S + 0,38R_t CS + 1,5R_t H$$

where; R_t is the degree of conversion at a particular temperature.

It is apparent from the above equation that R_t represents the percentage loss of water chemically combined within the tobermorite gel. In Figure V.1 the values of R_t are plotted against temperature. For a test temperature of 150°C the percentage loss of water from the tobermorite gel is 8%. For test specimens in the present investigation this represents a total percentage water loss of approximately 1,5% *. It is possible, therefore, that even at a test temperature of 150°C the most tightly held adsorbed water (i.e. the intercrystalline water between gel particles and intracrystalline zeolitic water[34]) is not removed from the cement gel.

At test temperatures of 250°C and 400°C the total percentage water loss of test specimens is greater than the total amount of water not chemically combined within the cement paste. From Figure V.1 it is apparent that at these temperature levels the loss of chemically combined water from tobermorite gel is highly significant. Furthermore, dehydration of calcium hydroxide may contribute to the water loss at 400°C: Figure V.1 illustrates the degree of conversion (R_{CH}) of calcium hydroxide in an idealized cement paste. However, the water loss due to dehydration of calcium hydroxide at a temperature of 400°C is negligible in comparison with the loss of chemically combined water from the tobermorite gel.

It is interesting to compare:

(i) the water loss at 70°C with that at 100°C,
(ii) the water loss at 100°C with that at 150°C,
(iii) " " " " " " " " 250°C,
(iv) " " " " " " " " 400°C.

This is done by plotting for each of (i) to (iv) above, the difference in percentage water loss at a particular time during the heating period against the logarithm of heating time. Figure V.2 and Figure V.3 illustrate these graphs for test specimens made from the concrete mix BCY and mortar mix BMY respectively, Figure V.4 and Figure V.5 the graphs for mixes CCX and CMX respectively, and Figure V.6 and Figure V.7 the graphs for mixes CCY and CMY. For each of the above diagrams the curves commence at the time at which the test temperatures became approximately constant.

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* The total percentage chemically combined water was approximately 30%. Of this amount 60% is chemically combined within tobermorite gel[86] and 40% is chemically combined within calcium hydroxide.

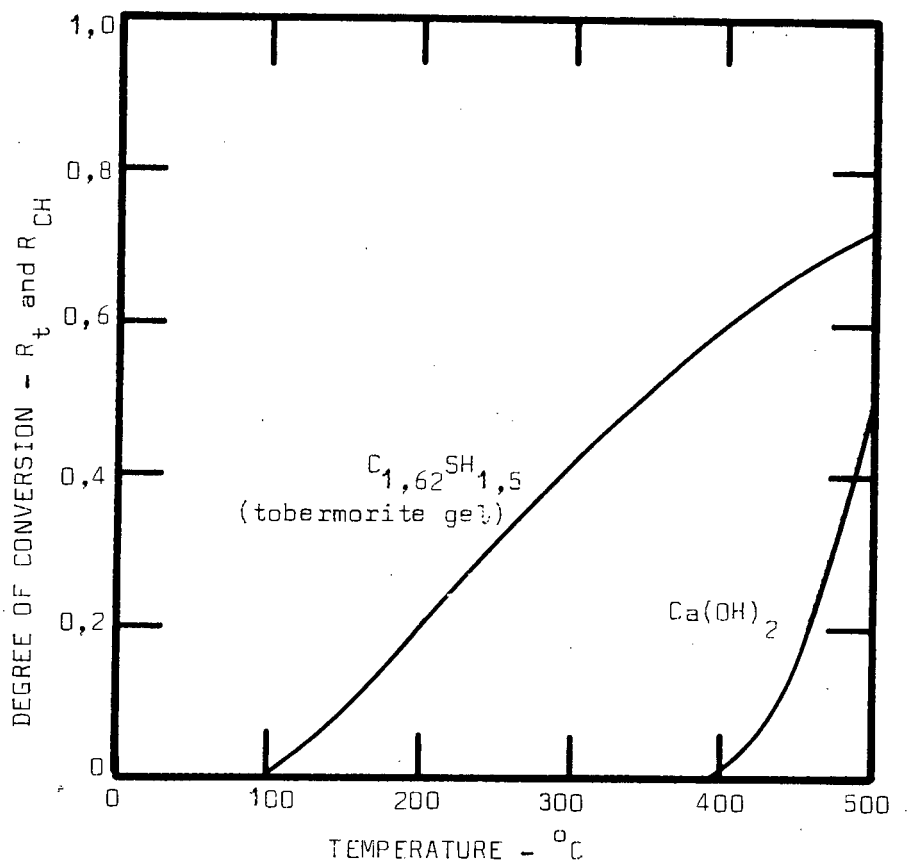

FIG.V.1: The degree of conversion (dehydration) of tobermorite gel and calcium hydroxide respectively in an idealized cement paste heated to various temperature levels.

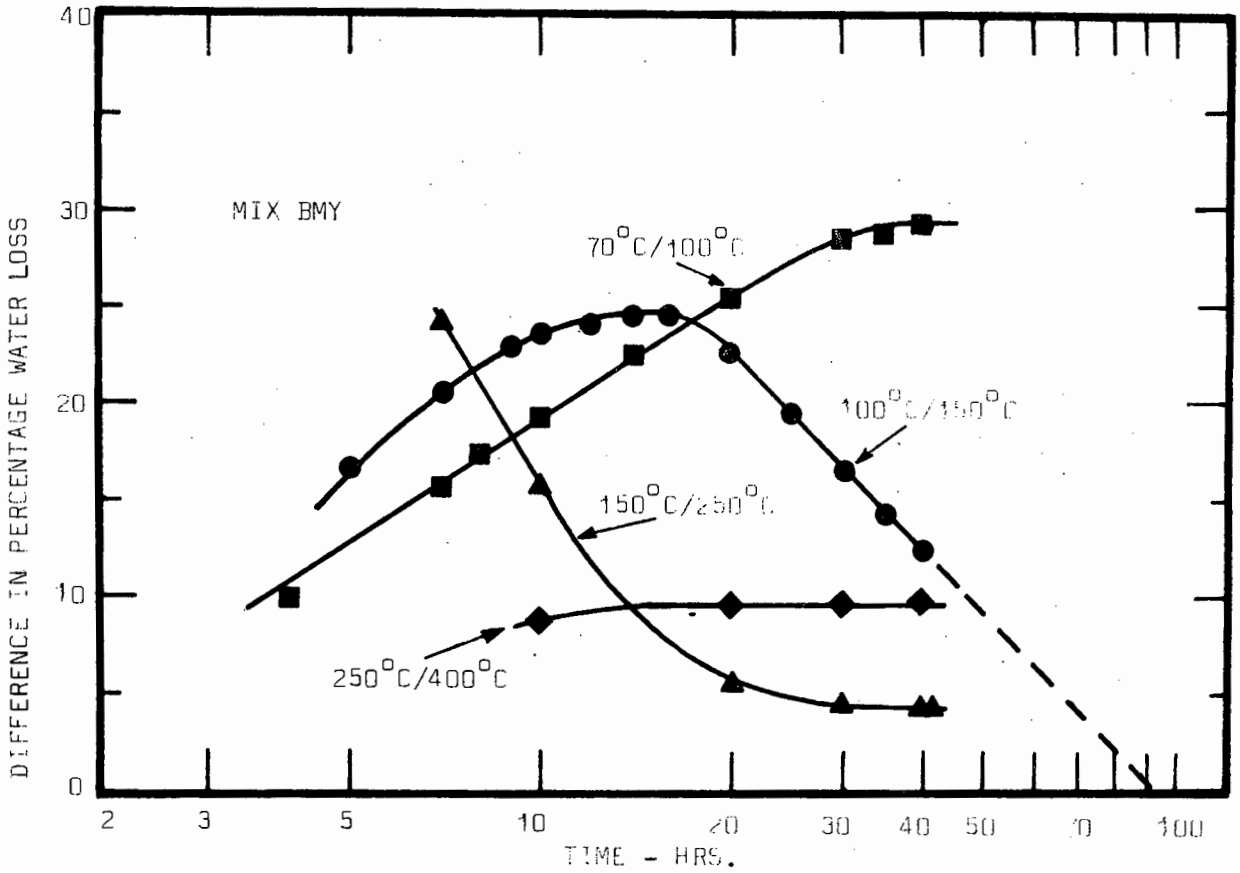

FIG.V.2: The difference between the percentage Water Loss at a particular time for test specimens heated to the indicated temperature levels.

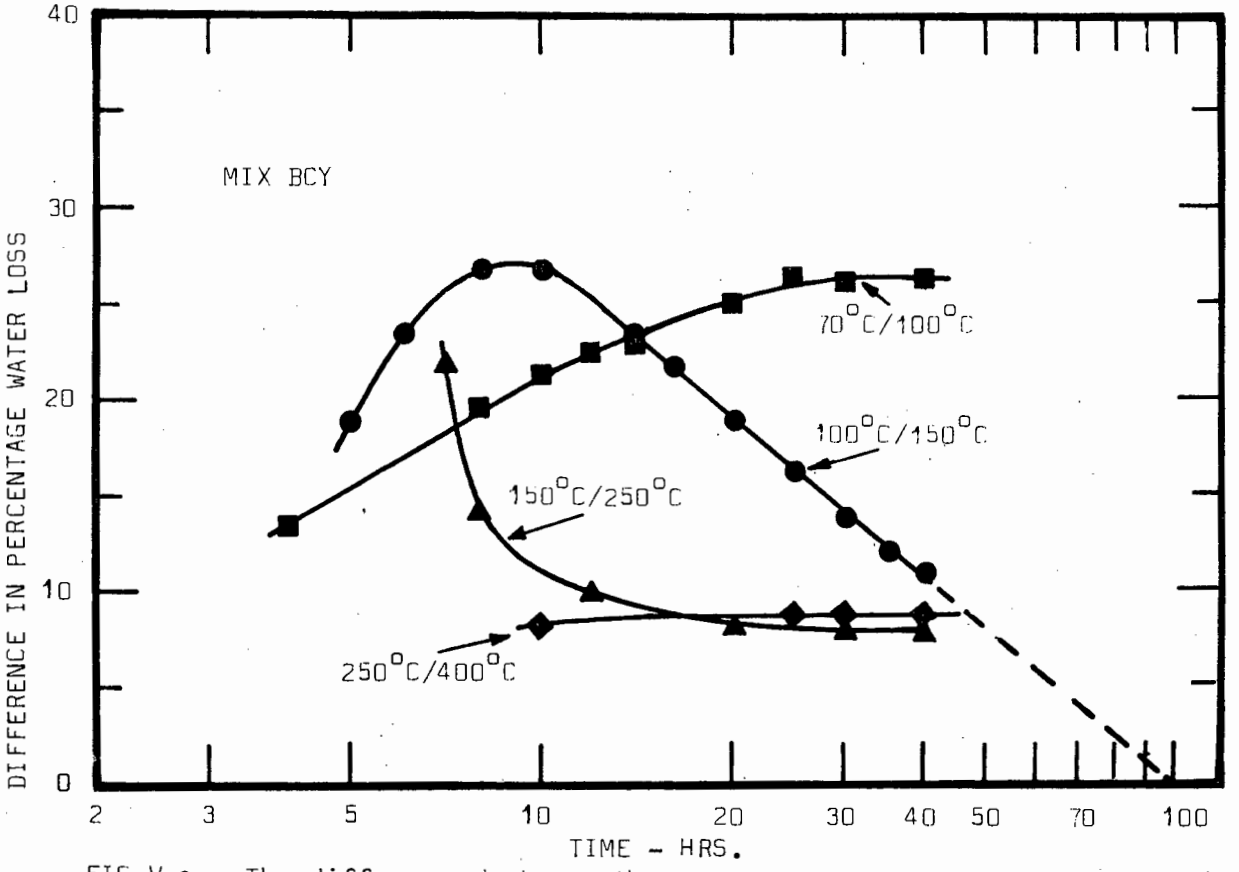

FIG.V.3: The difference between the percentage Water Loss at a particular time for test specimens heated to the indicated temperature levels.

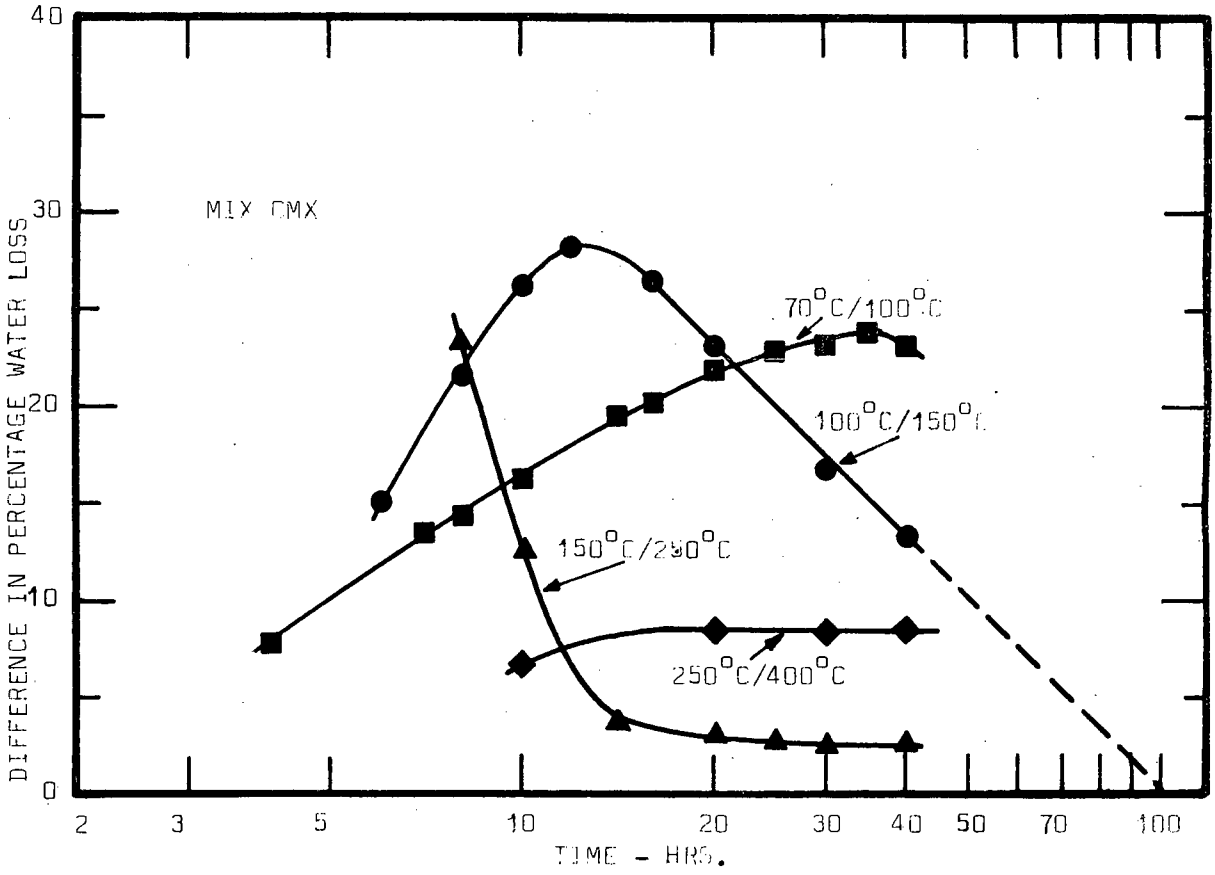

FIG.V.4: The difference between the percentage Water Loss at a particular time for test specimens heated to the indicated temperature levels.

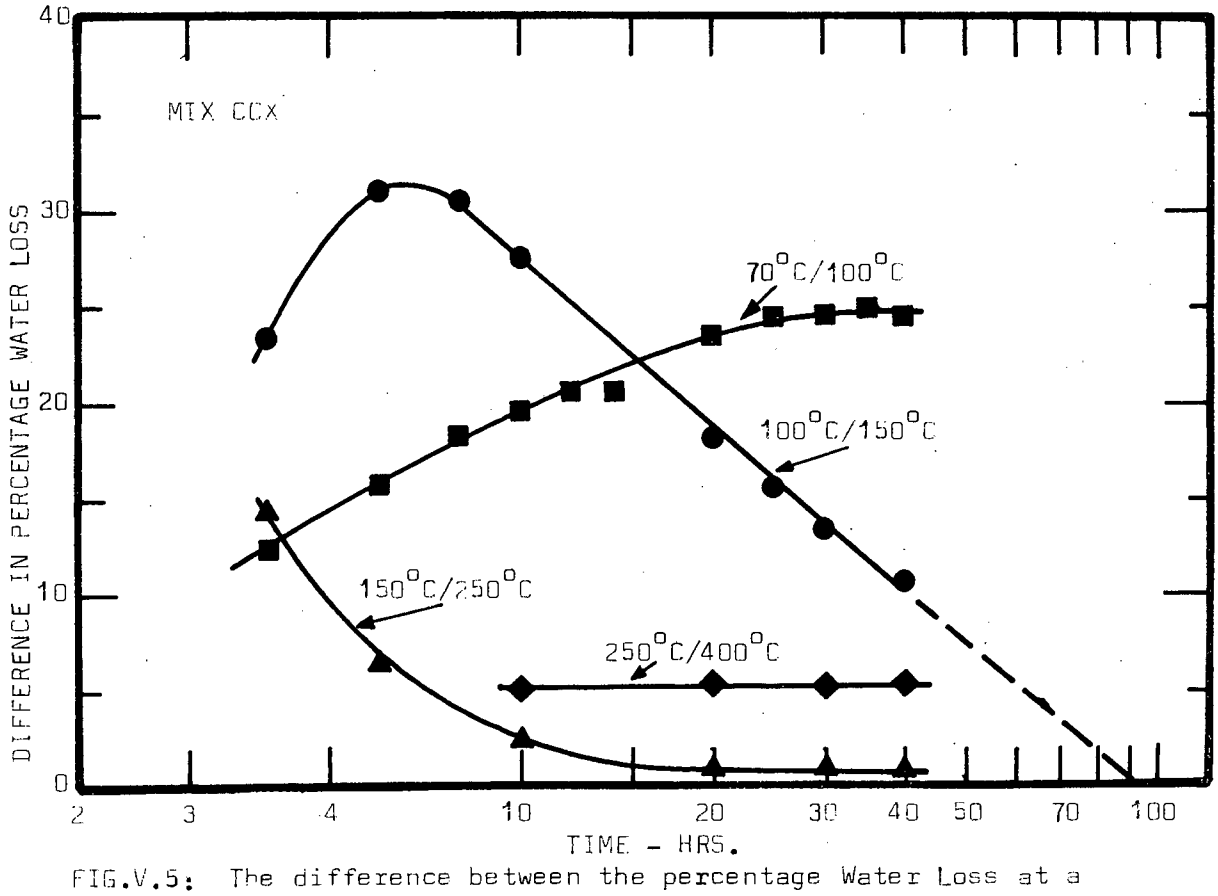

FIG.V.5: The difference between the percentage Water Loss at a particular time for test specimens heated to the indicated temperature levels.

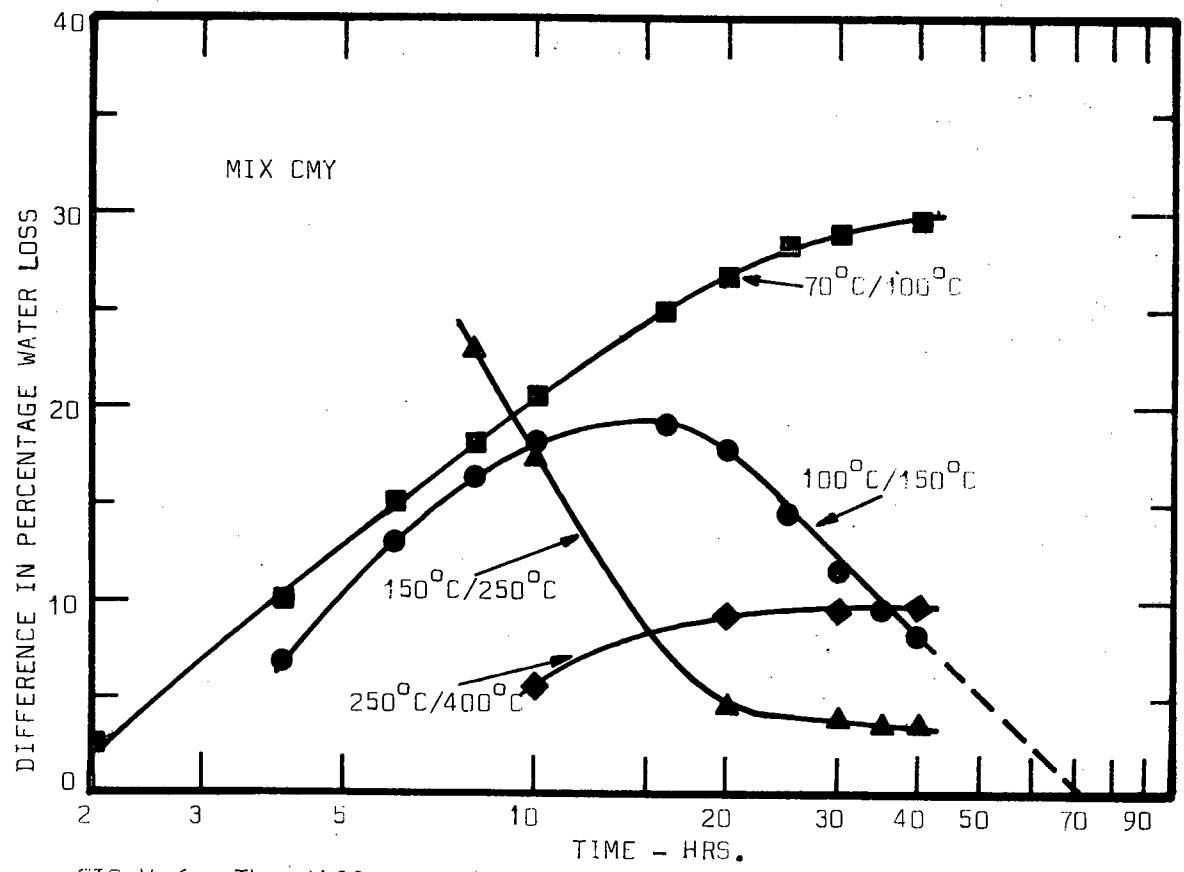

FIG.V.6: The difference between the percentage Water Loss at a particular time for test specimens heated to the indicated temperature levels.

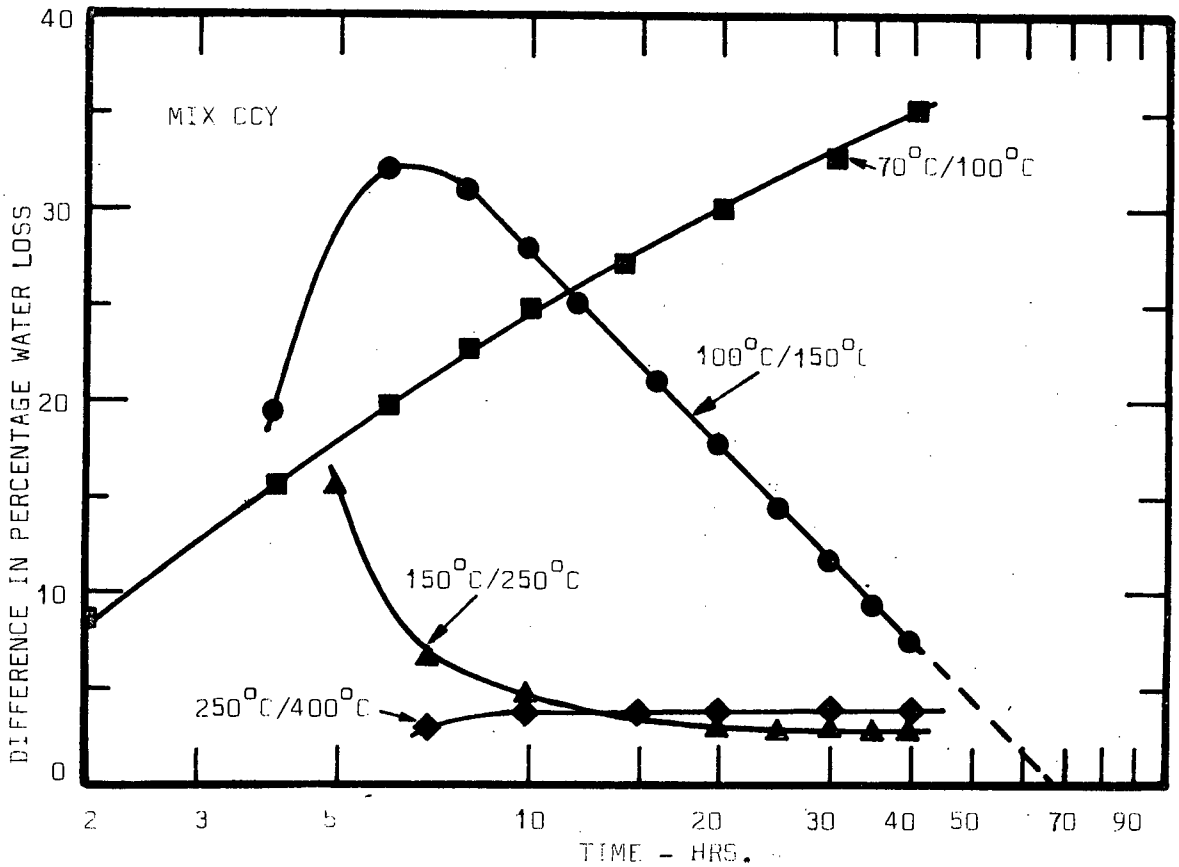

FIG.V.7: The difference between the percentage Water Loss at a particular time for test specimens heated to the indicated temperature levels.

From Figure V.2 to Figure V.7 it is apparent that:

(i) The difference in water loss between test specimens heated to 70°C and test specimens heated to 100°C increases with time during the heating period, i.e. it appears that the water loss of specimens heated to 70°C will never approach the water loss of specimens heated to 100°C.

(ii) The difference between the water loss of test specimens heated to 100°C and the water loss of test specimens heated to 150°C decreases most significantly with time during the heating period. By extrapolating these curves (Figure V.2 to Figure V.7) it appears that after a heating period of between 70 hrs and 100 hrs at 100°C, the water loss of test specimens heated to 100°C will be approximately the same as the water loss of test specimens heated to 150°C. However, it should be remembered that the percentage loss of chemically combined water at 100°C is not the same as that at 150°C. In this regard Wilson and Martin[85] have shown that the percentage water retained by specimens heated to constant mass at temperatures of 100°C and 150°C respectively, are significantly different. This is also apparent from the results of Harmathy[86] shown diagramatically in Figure V.1.

(iii) The difference between the percentage water loss at 150°C and the percentage water loss at 250°C first decreases with time during the heating period and then remains approximately constant at a value between 1% and 7,5%. It is thought that this difference in water loss is due to the additional loss of chemically combined water and loss of the most strongly adsorbed intercrystalline and intracrystalline zeolitic water.

(iv) The difference between the percentage water loss at 250°C and that at 400°C is approximately constant at a value between 4% and 10%. It is almost certain that this difference is due solely to the additional loss of chemically combined water.

It is not possible to corroborate the above findings with water loss results reported by other investigators[29, 38, 68, 85]. This is because usually:

(i) The investigators did not determine the non-evaporable water content of test specimens, i.e. it is not possible to calculate the degree of hydration and therefore neither W_g nor W_c can be calculated.

(ii) Test specimens were not maintained at a particular temperature level sufficiently long to achieve approximate moisture equilibrium.

1.2 The water loss of test specimens removed from the furnace at various times during the heating period and cooled before weighing

At all temperature levels this water loss data is usually in good agreement with the water loss measure continuously on test specimens during the heating period. The data is statistically analysed in PART IV. For test temperatures of 150°C and below, the analysis indicates that the water loss of test specimens increases with time during the heating period. This is similar to the trend exhibited by the water loss data discussed in 1.1 above.

The statistical analysis of the water loss data of test specimens heated to either 250°C or 400°C and removed from the furnace at the various test times during the heating period does not indicate that the water loss increases during the heating period. This is probably because the water loss which occurred whilst the temperature level remained constant at either 250°C or 400°C is small compared to the random variation of water loss between test specimens removed at the various test times.

The statistical analysis also indicates that the percentage water loss of heated concrete test specimens was usually equal to the percentage water loss of heated mortar test specimens.

1.3 The water loss of test specimens cooled at the various test times during the heating period and re-immersed in water for 7 days

Test specimens did not attain 100% saturation during the re-immersion period. The data indicates that for test temperatures of 70°C, 100°C and 150°C the water loss after re-immersion ranged from 2,8% to 5%, 3,7% to 5,5% and 5,1% to 7,8% respectively. Test specimens cooled from test temperatures of 250°C and 400°C exhibit a water loss after re-immersion of between 3,2% and 6,2%, and 1,3% and 2,9%, respectively. It is apparent that the water loss of specimens re-immersed after cooling from either 250°C or 400°C is significantly lower than the water loss of test specimens which were re-immersed after cooling from 150°C. A possible explanation for this behaviour is that micro-cracking * occurred within test specimens cooled from either 250°C or 400°C. The fact that the water loss after re-immersion is less for test specimens cooled from 400°C than for test specimens cooled from 250°C, substantiates this explanation.

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* This is discussed in CHAPTER 2 and CHAPTER 3.

CHAPTER 2 : THE LINEAR DEFORMATION OF HEATED TEST SPECIMENS

2.1 Test specimens which underwent drying during heating

The linear deformation of concrete and mortar test specimens which underwent drying at temperatures of either 70°C, 100°C or 150°C always decreases during the heating period, i.e. a contraction occurs during the time when the test temperature remains constant. At test temperatures of 250°C and 400°C both the concrete and mortar test specimens usually exhibit only a gradual contraction during the heating period.

The decrease in linear deformation during the heating period is due to water loss which occurs during heating. In this regard it is shown in PART I that the loss of either evaporable water or non-evaporable water causes a contraction of cement paste. Furthermore, the contraction which results from the loss of non-evaporable water may be many times greater than the contraction resulting from the removal of water from the gel pores and capillary pores: Lankard[38] reports results which indicate that the contraction accompanying the loss of all evaporable water from a cement paste is approximately 0,2% whereas the contraction accompanying the loss of non-evaporable water at a test temperature of 250°C is approximately 1%.

From the water loss results reported in CHAPTER 1 it appears likely that the contraction of concrete and mortar specimens at temperatures of either 70°C, 100°C or 150°C is primarily due to the loss of water from the capillary pores and gel pores. In this regard Lankard[38] is of the opinion that "the cement gel phase is exceedingly mobile during the time in which evaporable water is being removed during first-time drying. It is conceivable that during drying the individual gel crystallites are continually changing their positions relative to the remainder of the gel, the freedom of motion dictated to some extent by the degree of bonding with other solid elements of the gel (either solid-solid bonding or through a mutually shared adsorped water layer). It is envisioned that the movement of the gel crystallites in response to strain accompanying the removal of evaporable water is facilitated by the presence of adsorped layers on their surface. As the last vestiges of the evaporable water leave the paste the mobility of the gel is sharply curtailed since the bonds between gel crystallites are predominantly solid-solid and no adsorped layer remains to act as a lubricant between two solid surfaces in close proximity". It appears, therefore, that for test temperatures up to 150°C the contraction of cement paste relative to aggregate is accommodated by the fact that the cement gel is highly mobile during the removal of evaporable water, i.e. the stresses

which may develop as a result of relative movement between the cement paste and aggregate are probably relieved by creep. In this regard it was illustrated in PART I : CHAPTER 1 that both specific creep and creep rate is usually higher at elevated temperature than at normal temperature. It follows that this effect will also accommodate any stresses which may arise from the difference between the coefficient of thermal expansion of cement paste and aggregate.

The water loss data discussed in CHAPTER 1 indicate that the water loss at 250°C and 400°C probably includes a considerable proportion on non-evaporable water. The removal of non-evaporable water during the heating period should result in greater contraction of concrete or mortar test specimens than the contraction which accompanies the loss of evaporable water. Referring to the summarised linear deformation curves reported in PART III : CHAPTER 8 it is apparent that the contraction which occurred during the heating period for test specimens heated to either 250°C or 400°C is usually less than the contraction which occurred for test specimens heated to 150°C. This indicates that for concrete and mortar specimens heated to either 250°C or 400°C;

(i) a considerable proportion of the test specimen contraction occurred during the heating period before the desired temperature level had been attained, and/or

(ii) the contraction resulting from the loss of non-evaporable water is accompanied by microcracking of the concrete and mortar test specimens.

It is thought that both (i) and (ii) above contribute to the observed behaviour of linear deformation at test temperatures of either 250°C or 400°C. The second of the abovementioned explanations may be inferred from the conclusion of Lankard[38] that after complete removal of evaporable water the microstructure of heated cement paste is fixed by the predominance of solid-solid bonding, i.e. the paste can no longer be considered as mobile and the stresses resulting from contraction of cement paste relative to aggregate particles cannot be relieved by the creep mechanism which is operative at temperature levels at which the intercrystalline adsorbed water facilitates creep. Consequently, the stresses are relieved by microcracking, either within the paste or at a paste aggregate interface. In this regard it is shown in PART 1 : CHAPTER 4 that at temperatures of either 250°C or 400°C the tensile stresses which may result from contraction of cement paste relative to aggregate particles are far greater than the tensile stresses which a Portland cement paste can withstand. (The values of cement paste contraction[7] used in the calculation illustrated in PART 1 : CHAPTER 4 are lower than the values

reported by Lankard[38]. This is probably due to the effects of heating rate[38].)

The conclusion that microcracking occurred within test specimens heated to 250°C and 400°C is further substantiated by the fact that;

(i) it was found that the water loss of test specimens cooled from either 250°C or 400°C and immersed in water for 7 days, is less than the water loss of specimens immersed in water after cooling from 150°C, and

(ii) the residual linear deformation * of both concrete and mortar test specimens cooled from either 250°C or 400°C is an expansion relative to the residual linear contraction which occurred for specimens cooled from 150°C. The residual linear deformation results are discussed in greater detail in the following chapter : CHAPTER 3.

In the above discussion concerning the microcracking of test specimens heated to 250°C and 400°C, only the contraction of the cement paste relative to aggregate particles during the loss of non-evaporable water is considered. However, the difference in thermal expansion between the cement paste and aggregate may also contribute to the microcracking at these temperature levels. This becomes clear when it is considered that the coefficient of thermal expansion of cement paste decreases as complete dryness is approached, whereas the coefficient of thermal expansion of the aggregate increases with temperature**. The approximate magnitude of the differential expansion and the resulting stresses can be calculated. For a completely dry paste Meyers[10] reports a coefficient of thermal expansion of $10{,}25 \times 10^{-6}$ per deg. C. The coefficient of thermal expansion of the fine aggregate used in the present investigation was $11{,}0 \times 10^{-6}$ per deg. C at 250°C and $12{,}80 \times 10^{-6}$ per deg. C at 400°C. Using a datum temperature of 30°C, the differential expansion between cement paste and fine aggregate is therefore:

$= (11{,}00 - 10{,}25) \times 220 \times 10^{-6}$ mm/mm

$\div$ 0,017% at 250°C, and

$= (12{,}80 - 10{,}25) \times 370 \times 10^{-6}$ mm/mm

= 0,094% at 400°C.

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* the linear deformation of test specimens after cooling to the datum temperature.

** Reported in PART III : CHAPTER 8.

In PART I : CHAPTER 4, theoretical values of the tensile stresses which may occur due to a contraction of cement paste relative to aggregate are calculated from the stress coefficients reported by Hsu[48]. The same stress coefficients apply for the case where aggregate expands relative to cement paste. Using the above values of differential expansion and assuming that the values of Young's modulus and Poisson's ratio at 250°C and 400°C are the same as those used in PART I : Table I.7, the following stresses can be calculated:-

(i) The maximum tensile stress within the cement paste;

= 2,98 MPa at 250°C, and

= 13,24 MPa at 400°C.

(ii) The maximum tensile stress at the paste/aggregate interface;

= 0,83 MPa at 250°C, and

= 3,70 MPa at 400°C.

From the above calculation it appears likely that the difference in thermal expansion between the cement paste and fine aggregate contributes to the microcracking within test specimens at a test temperature of 400°C. It is thought that this effect is of greater importance during temperature cycling than during the period when test specimens are heated for the first time. This is because specimens contain intercrystalline adsorbed water for a considerable portion of the first-time heating period: the intercrystalline water facilitates creep and consequently the stresses arising from incompatible expansion between cement paste and fine aggregate are relieved to a certain extent.

At a temperature of 250°C the calculated stresses are much lower than those calculated for a test temperature of 400°C. It does appear that these stresses are not sufficiently great to cause microcracking within test specimens. However, it must be remembered that if these stresses are not relieved by creep, they may nevertheless affect the physical properties of the test specimens. With regard to the above stress calculation it should be noted that the stresses were calculated for the two-phase material consisting of cement paste and fine aggregate. It is likely that much higher stresses will occur due to incompatible expansions in the three-phase system * consisting of cement paste, mortar and coarse aggregate. This becomes apparent when it is considered that;

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* It is not possible to calculate these stresses from the stress analysis reported by Hsu[48].

(i) at 250°C the differential expansion between the coarse aggregate* and mortar is approximately 0,051%, and

(ii) at 400°C the differential expansion between the coarse aggregate* and mortar is approximately 0,148%.

i.e. at both 250°C and 400°C the differential expansion is of greater magnitude than the values used in calculating the stress due to incompatible expansion between cement paste and fine aggregate. Consequently, it does appear that at temperatures of both 250°C and 400°C the differential expansion between fine aggregate and cement paste as well as that between coarse aggregate and mortar is significant.

2.2 Test specimens which remained fully saturated during heating

The linear expansion of concrete and mortar test specimens which remained fully saturated at temperatures of either 70°C or 100°C increases gradually during the time that the temperature remained constant at the test temperature level. The increase in linear expansion during the heating period is widely different for the various concrete and mortar mixes. Furthermore, there is no definite trend as to whether the increases are greater for the concrete mixes or the mortar mixes. This is probably because part of the increase in linear expansion occurred during the time period when the test specimens were being heated to the test temperature.

However, the data obtained from residual linear deformation measurements (discussed in CHAPTER 3) indicate that the residual expansion of mortar test specimens is approximately twice as great as the residual expansion of concrete test specimens. These results also show that the residual linear expansion is greater for specimens heated to 100°C than for specimens heated to 70°C. The first of the abovementioned findings indicates that the gradual increase in linear expansion does not occur as a result of a physical or chemical reaction associated with the coarse aggregate. Consequently, the observed expansion was due to an effect resulting from either;

(i) a chemical reaction within the cement paste, or

(ii) an interaction between the cement paste and fine aggregate.

Both the above effects are thought to contribute to the increase in linear

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* Using the coefficient of thermal expansion values for coarse aggregate as reported in PART III.

expansion of saturated specimens maintained at a test temperature of either 70°C or 100°C. Figure V.8 and Figure V.9 show the linear deformation of neat cement paste test specimens * which remained fully saturated during heating at temperatures of 70°C and 100°C respectively. It is apparent that at both 70°C and 100°C the cement paste test specimens exhibit an increase in linear expansion during the heating period. Upon cooling to the datum temperature, the cement paste specimens exhibit a residual expansion. Consequently it appears that the residual expansion of saturated concrete and mortar test specimens heated to either 70°C or 100°C is the result of a chemical reaction which occurred within the cement paste. The increase in linear expansion of neat cement paste specimens could be associated with an increase in the $CaO : S_iO_2$ ratio of the tobermorite gel[71]. This reaction occurs when Portland cement paste is cured in saturated steam at 100°C. The reaction results in transformation of the tobermorite gel ($C_{1,62}\ SH_{1,5}$) into crystalline $C_6S_2H_3$. There is evidence, too, that under these conditions increased amounts of alumina and sulphur trioxide pass into the tobermorite gel[90]. Imlach[89] reports, however, that in the presence of siliceous aggregate, the reaction which occurs in saturated specimens heated to 100°C is the formation of 11.3 Å tobermorite ($C_5S_6H_5$). In the present investigation, both the coarse and fine aggregate contained approximately 75% S_iO_2. Consequently, it appears that for concrete and mortar test specimens which remained fully saturated at either 70°C or 100°C, the increase in linear expansion during the heating period may have been caused by the formation of 11.3 Å tobermorite.

However, it is thought that the abovementioned effect may not be the only factor which causes an increase in the linear expansion of saturated test specimens at temperatures of either 70°C or 100°C: the difference between the coefficient of thermal expansion of the constituents may also contribute to the increase in linear expansion in that creep of the cement paste to relieve stresses which result from incompatible expansion of the constituents may occur. In this regard it should be remembered that in the stress analysis reported by Hsu[48], the stresses which occur when cement paste expands relative to aggregate are greater than the stresses which result from cement paste contraction relative to aggregate.

Consider the two-phase material consisting of cement paste and fine aggregate. From Figure V.8 and Figure V.9 the coefficient of thermal expansion of cement paste at 70°C and 100°C may be determined. These values are

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* The cement paste specimens had a $^{w}/_{c}$ ratio of 0,26. The manufacture and subsequent treatment of these specimens was exactly the same as that for the concrete and mortar test specimens. The given results are the mean of three independent determinations.

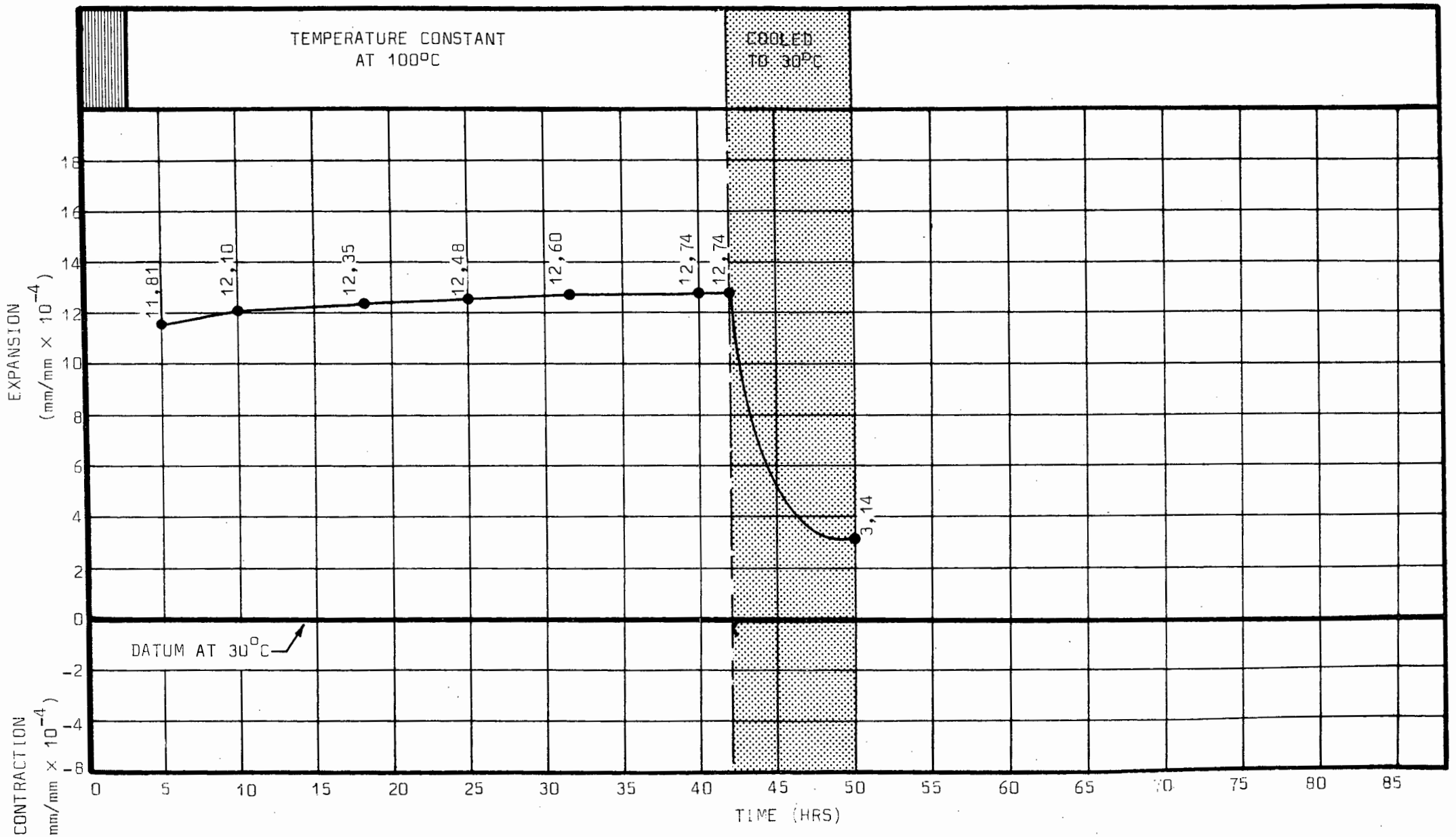

FIG.V.8: The linear deformation of neat cement paste test specimens heated to 70°C: specimens fully saturated during heating.

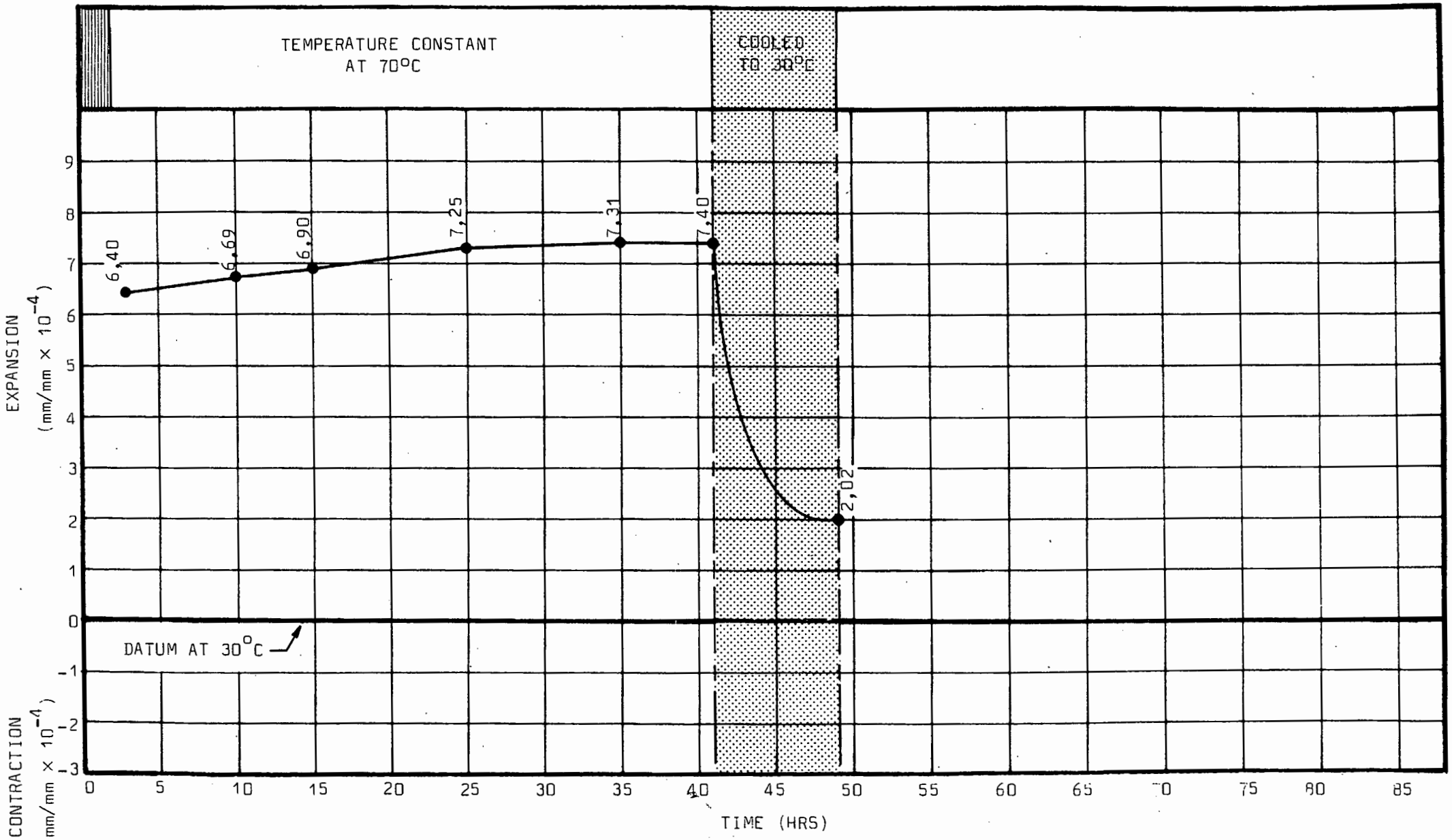

FIG.V.9: The linear deformation of neat cement paste test specimens heated to 100° C: specimens fully saturated during heating.

$13,45 \times 10^{-6}$ per deg. C and $13,71 \times 10^{-6}$ per deg. C respectively.* In the present investigation the coefficient of thermal expansion of the fine aggregate was $9,03 \times 10^{-6}$ per deg. C at 70°C and $9,18 \times 10^{-6}$ per deg. C at 100°C. Consequently the differential expansion was

$$= (13,45 - 9,03) \times 40 \times 10^{-6} \text{ mm/mm}$$

$$= \underline{0,018\% \text{ at } 70^{\circ}C}, \text{ and}$$

$$= (13,71 - 9,18) \times 70 \times 10^{-6} \text{ mm/mm}$$

$$= \underline{0,032\% \text{ at } 100^{\circ}C}.$$

At both 70°C and 100°C the cement paste expands relative to the aggregate. Referring to Table I.7 in CHAPTER 4 : PART I, it is possible to calculate the approximate magnitude of the tensile stresses which may result from the above values of differential expansion. These values are:-

(i) The maximum tensile stress within the cement paste;

= 6,75 MPa at 70°C, and

= 11,47 MPa at 100°C.

(ii) The maximum tensile stress at the cement paste/aggregate interface;

= 6,52 MPa at 70°C, and

= 11,08 MPa at 100°C.

It is believed that during the heating period these stresses were relieved by creep and that this caused an increase in the linear expansion of test specimens. The fact that creep occurs is substantiated by the finding that both the creep rate[66] and the specific creep[62,64] of sealed concrete test specimens is two to three times greater at temperatures between 70°C and 100°C than at room temperature.

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* It must be pointed out that these values refer to a cement paste having a $^{w}/_{c}$ ratio of 0,26, i.e. the values may be different for the cement paste used in the concrete or mortar test specimens.

CHAPTER 3 : RESIDUAL LINEAR DEFORMATION AND COEFFICIENT OF THERMAL EXPANSION OF CONCRETE AND MORTAR TEST SPECIMENS

3.1 Summary of results

The residual linear deformation was determined for concrete and mortar test specimens heated to the various temperatures and either;

(i) removed from the furnace (waterbath) at the various test times during the heating period and cooled before testing, or

(ii) removed from the furnace (waterbath) at the various times during the heating period, cooled and immersed in water for 7 days before testing.

For (i) above it was found that a residual linear contraction occurred for test specimens which underwent drying at either 70°C, 100°C or 150°C: the higher the temperature the greater the residual linear contraction of test specimens. Test specimens cooled from 250°C also exhibit a residual linear contraction. However, the residual contration of concrete and mortar specimens is less than the contraction which occurred for a test temperature of 150°C. Both concrete and mortar specimens cooled from 400°C underwent a residual expansion. The residual expansion was in some instances as much as six times greater than the maximum residual contraction which had occurred for test specimens cooled from the lower temperature levels. Test specimens whichremained fully saturated during heating and were tested as under (i) above exhibit a residual expansion after cooling from either 70°C or 100°C. In general, the residual expansion of saturated concrete and mortar specimens is greater for specimens cooled from 100°C than for specimens cooled from 70°C.

For (ii) above it was found that test specimens cooled from either 70°C, 100°C or 150°C exhibit a residual contraction, i.e. the contraction which occurred during the heating period is not eliminated by re-immersing test specimens in water. In this regard it is particularly interesting that the residual contraction for specimens which were heated to 150°C and underwent treatment as under (ii) above is less than the residual contraction of test specimens which were heated to 100°C and tested as under (ii). Both concrete and mortar test specimens cooled from either 250°C and immersed in water for 7 days exhibit a residual expansion whereas these test specimens had exhibited a residual contraction when tested immediately after cooling from 250°C. Specimens cooled from 400°C and tested after 7 days in water always exhibit a residual expansion. This residual expansion was approximately twice as

as great as the residual expansion which occurred for specimens tested immediately after cooling from 400°C.

It was found from a statistical analysis * of the abovementioned results that:

(i) In instances where the residual linear deformation of test specimens was a contraction, the contraction was always greater for mortar test specimens than for concrete test specimens, and

(ii) In instances where the residual linear deformation of test specimens was an expansion, the expansion was always greater for mortar test specimens than for concrete specimens.

The statistical analysis of the abovementioned results also indicates that for test specimens which were re-immersed in water after cooling:

(i) The residual contraction of mortar test specimens cooled from either 70°C or 100°C and immersed in water for 7 days is greater than the residual contraction of concrete test specimens which were cooled from the corresponding temperature levels, and immersed in water for 7 days.

(ii) The residual contraction of mortar test specimens immersed in water after cooling from 150°C is not significantly different from the residual contraction of concrete specimens subjected to similar treatment.

(iii) In instances where the residual linear deformation of test specimens was one expansion (i.e. for specimens cooled from 250°C and 400°C) the expansion was always greater for the mortar test specimens that for concrete test specimens.

It was also found that for test specimens which were tested immediately after cooling, as well as for specimens tested after cooling and 7 days immersion in water;

(i) The residual linear deformation is usually dependent on the heating time, and

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* Reported in PART IV.

(ii) at a particular temperature the residual linear deformation exhibited by test specimens made from the various concrete mixes (or mortar mixes) are significantly different.

3.2 The Effect of Heating Time

3.2.1 Specimens tested immediately after cooling

The effect of heating time on the residual linear deformation is illustrated graphically in Figure V.10 and Figure V.11. In Figure V.10 the mean coded values * of linear deformation (i.e. the coded values obtained by averaging across mixes) are illustrated for test specimens made from the concrete mixes. Figure V.11 illustrates the data for mortar test specimens. For a particular test temperature two mean coded values are shown. These are the minimum value and the maximum value that were obtained from tests performed at the various test times during the heating period. At certain of the test temperatures an arrow is drawn from the minimum value to the maximum value: this shows that the analysis reported in PART IV indicates a statistically significant trend during the heating time at the particular test temperature. The direction indicated by the arrow shows whether the linear deformation increases or decreases during the heating period.

From Figure V.10 and Figure V.11 it is apparent that:

(i) For concrete and mortar test specimens which underwent drying at test temperatures of either 70°C, 100°C or 150°C the residual linear contraction increases during the heating period. This trend is similar to the trend exhibited by the linear deformation of test specimens whilst hot. (Discussed in CHAPTER 2.)

(ii) The residual linear expansion of specimens cooled from 400°C becomes greater for specimens removed from the furnace at successive test times during the heating period. This is the opposite to the trend exhibited by the linear deformation of specimens tested whilst hot at 400°C. It is thought that the increase in linear expansion illustrates that microcracking occurred

(a) progressively during the heating period at 400°C, and

(b) during the time when test specimens were cooled to the datum temperature.

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* The coded values of linear deformation are the actual measured values.

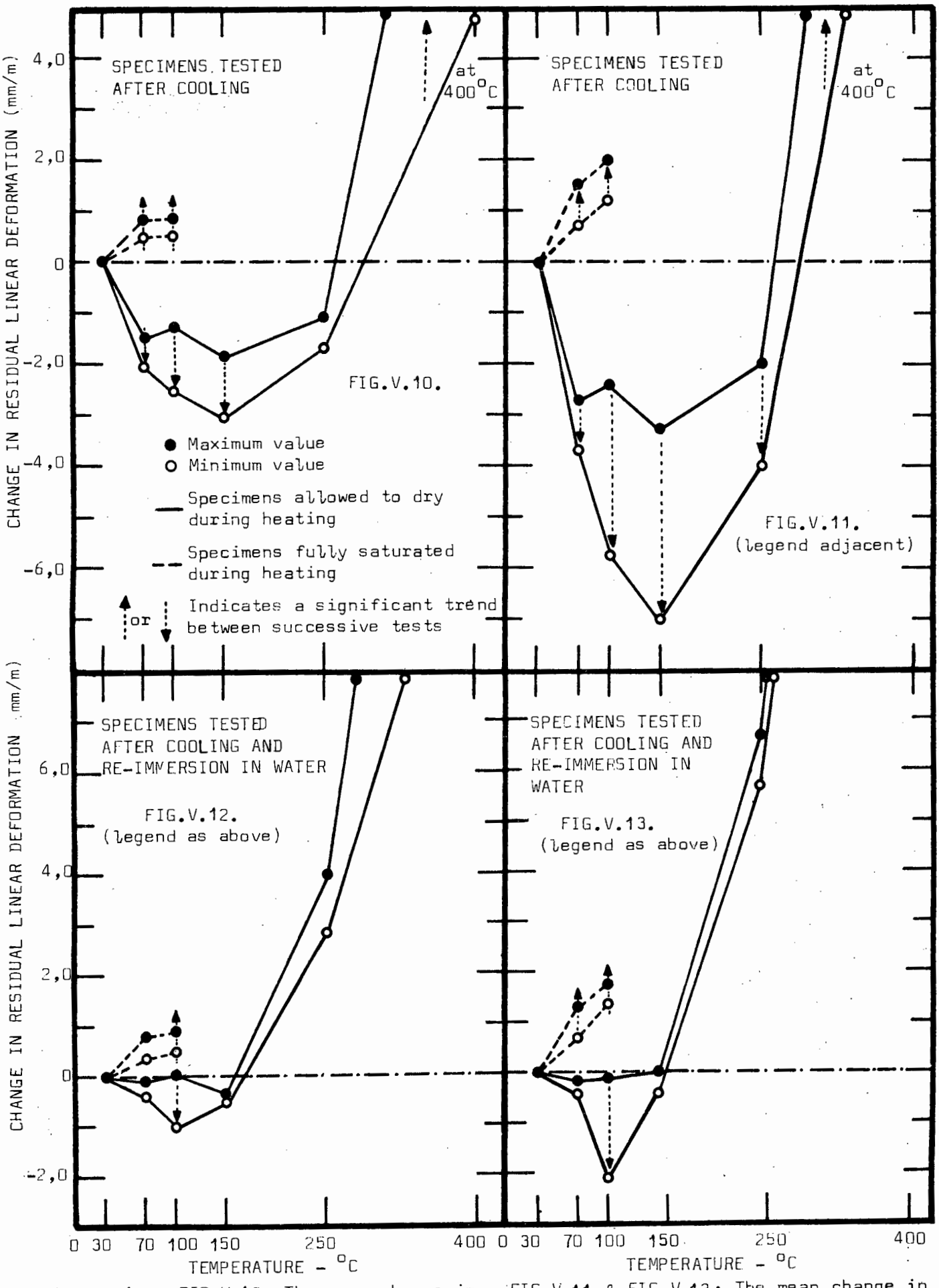

FIG.V.10.& FIG.V.12: The mean change in residual linear deformation of test specimens made from the three concrete mixes.

FIG.V.11.& FIG.V.13: The mean change in residual linear deformation of test specimens made from the three mortar mixes.

Either (a) or (b) alone cannot explain the linear deformation behaviour of specimens during heating as well as after cooling from 400°C. It is also particularly interesting that the residual linear expansion of mortar specimens cooled from 400°C is approximately twice as great as the residual linear expansion of concrete specimens cooled from 400°C. The mix proportions of the concrete mixes were such that the mixes contained approximately 50% coarse aggregate. Consequently, it appears that at 400°C the residual linear deformation of the concrete mixes is almost entirely dominated by the residual linear deformation of the mortar used in manufacturing the concrete mixes.

(iii) There is no significant trend to the residual contraction of concrete test specimens cooled from 250°C at successive test times during the heating period. However, the residual linear contraction of mortar test specimens cooled from 250°C increases for specimens removed at successive test times during the heating period. It is thought that for test specimens cooled from 250°C the factors which influence the residual linear deformation are the same as those which influence the residual linear deformation of specimens cooled from 400°C. This is inferred from the fact that the residual linear contraction of specimens cooled from 250°C is not as great as the residual contraction of specimens cooled from 150°C, i.e. it appears that microcracking occurred within test specimens during the heating period at 250°C. It is possible, though, that for specimens cooled from 250°C the difference between the coefficient of thermal expansion of paste and aggregate was not a significant factor in causing further microcracking when test specimens were cooled to the datum temperature. This is shown by a calculation of the tensile stresses which may theoretically occur when mortar test specimens are cooled from 250°C. The stress calculation was given in CHAPTER 2.

(iv) The residual linear expansion of both concrete and mortar test specimens which remained fully saturated at either 70°C or 100°C, increases for specimens tested at the successive test times during the heating period. The trend is similar to the trend exhibited by the linear deformation measured on test specimens whilst hot. The increase in linear expansion with time during the heating period was dicussed in CHAPTER 2.

3.2.2 Specimens tested after cooling and 7 days immersion in water

In Figure V.12 the mean coded values of residual linear deformation after cooling and re-immersion in water are illustrated for test specimens made from the concrete mixes. Figure V.13 illustrates the data for the mortar mixes. The mean coded values were obtained by averaging the coded values for the three concrete (or mortar) mixes. In each case the minimum value and the maximum value of linear deformation that occurred for test specimens removed at the successive test times during the heating period are shown. In instances where the statistical analysis (PART IV) indicates a significant trend to the residual deformation of specimens tested at successive test times during the heating period, the trend is shown by an arrow between the minimum and maximum values.

From Figure V.12 and V.13 it is apparent that for specimens which underwent drying during heating;

(i) The residual linear contraction of test specimens cooled from either 70°C, 100°C or 150°C is to a certain extent irreversible, i.e. after 7 days immersion in water the test specimens still exhibit a residual contraction. This irrecoverable contraction probably involves the closing of gaps between gel particles and results from the removal of water confined between[34] adjacent crystal surfaces (intercrystalline water *). The removal of water embedded within the crystal layers, (zeolitic intracrystalline** water) may also be a factor in causing irrecoverable contraction. Any contraction of such small inter-solid gaps causes an increase in the Van der Waals binding forces. It is also possible that in certain zones new chemical bonds (i.e. solid-solid bonds) may occur. Consequently upon re-immersion in water the water molecules cannot re-occupy the now closed original spaces. However, the abovementioned irrecoverable processes only became operative as almost complete dryness (i.e. dry with respect to the loss of evaporable water) of the concrete or mortar test specimens is approached. The above mechanism would thus only explain why the shrinkage of specimens heated to 150°C is irrecoverable since it is very likely that these test specimens lost some intercrystalline and intracrystalline water during the heating period.

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* 1-2 uni-molecular layers thick.

** Approximately 1 uni-molecular layer thick.

It appears that the abovementioned shrinkage mechanisms cannot account for the fact that test specimens which were heated to either 70°C or 100°C also exhibit irreversible shrinkage after re-immersion in water. An explanation for this behaviour is given by Ishai[34] who indicates that irrecoverability of shrinkage is possible even if test specimens are not at a stage of dryness where the most strongly held adsorbed water (i.e. the intercrystalline and intracrystalline water) is removed. Ishai[34] is of the opinion that "under prolonged hydrostatic compression * the adsorbed confined water squeezes out slowly, thereby causing a reduction in the small inter-solid gaps: this is similar to the irrecoverable creep mechanism under an external load".

It is particularly interesting in Figure V.12 and Figure V.13 that the residual contraction of both concrete and mortar specimens cooled from 150°C and immersed in water for 7 days is less than the residual linear contraction of test specimens immersed in water after cooling from 100°C. Furthermore the residual contraction of both concrete and mortar specimens cooled from 100°C and immersed in water for 7 days depends upon the heating time wheras the residual contraction of test specimens cooled from 150°C and immersed in water is not dependent on the heating time. This behaviour probably indicates that the drying shrinkage which occurred during the heating period at 150°C was accompanied by minor (sub-critical) microcracking[87]. When test specimens are re-immersed in water the decrease in surface energy of the crack (due to the adsorption of water on the surface of the crack) results in an increase in the length of the crack[88]. However, it is probable that the crack at this stage still falls into the sub-critical class, i.e. the sub-critical crack increases in size and attains a new sub-critical size. The dimension of a test specimens would thus increase in the direction perpendicular to the crack extension. Consequently, the overall magnitude of irreversible shrinkage and creep deformation is reduced by the expansion resulting from crack propagation after re-immersion in water.

(ii) The residual linear deformation of test specimens cooled from either 250°C or 400°C and immersed in water for 7 days, is an

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* The hydrostatic compression results from the recoverable shrinkage deformation of test specimens during the loss of pore water[34].

expansion. It is thought that this behaviour indicates beyond any doubt that microcracking occurred within these test specimens.

The reason for the beahviour of linear deformation is the same as that explained in (i) above. The expansion which occurs when test specimens are immersed in water are greater for specimens cooled from either 250°C or 400°C than for specimens cooled from 150°C since there were a greater number of sub-critical cracks in the test specimens which were dried at the higher temperature levels. Furthermore, it is probable that upon re-immersion of the 250°C and 400°C test specimens, the size of certain of the cracks attained the critical crack size and resulted in spontaneous propagation of the crack[87]. It should be noted that for test specimens which were cooled from 400°C and immersed in water, the increase in residual linear expansion could have occurred as a result of the re-hydration of $Ca(OH)_2$. However, it is apparent from Figure V.1 in CHAPTER 1 that the dehydration of $Ca(OH)_2$ at 400°C is probably less that 2% by mass of $Ca(OH)_2$. Also, the fact that a residual expansion occurred for specimens which were tested immediately after cooling from 400°C, indicates that microcracking was a significant factor in the linear deformation behaviour of these test specimens.

(iii) The maximum and minimum mean coded values of residual expansion for specimens which remained fully saturated at either 70°C or 100°C, and were cooled and re-immersed in water for 7 days, are not significantly different from the corresponding values for specimens tested immediately after cooling. It appears, therefore, that the physical/chemical reaction which caused this residual expansion is irreversible.

3.3 The residual linear deformation of the various concrete (or mortar) mixes

The mean coded values of residual linear deformation are shown in Figure V.14 for test specimens made from the three concrete mixes BCY, CCX and CCY respectively. The mean coded value is calculated as the mean of the four linear deformation measurements on test specimens cooled at various test times during the heating period. Figure V.15 illustrates the mean coded values of linear deformation for test specimens made from mortar mixes BMY, CMX and CMY respectively. Figure V.16 and Figure V.17 show the mean coded values of residual deformation for specimens cooled from the various

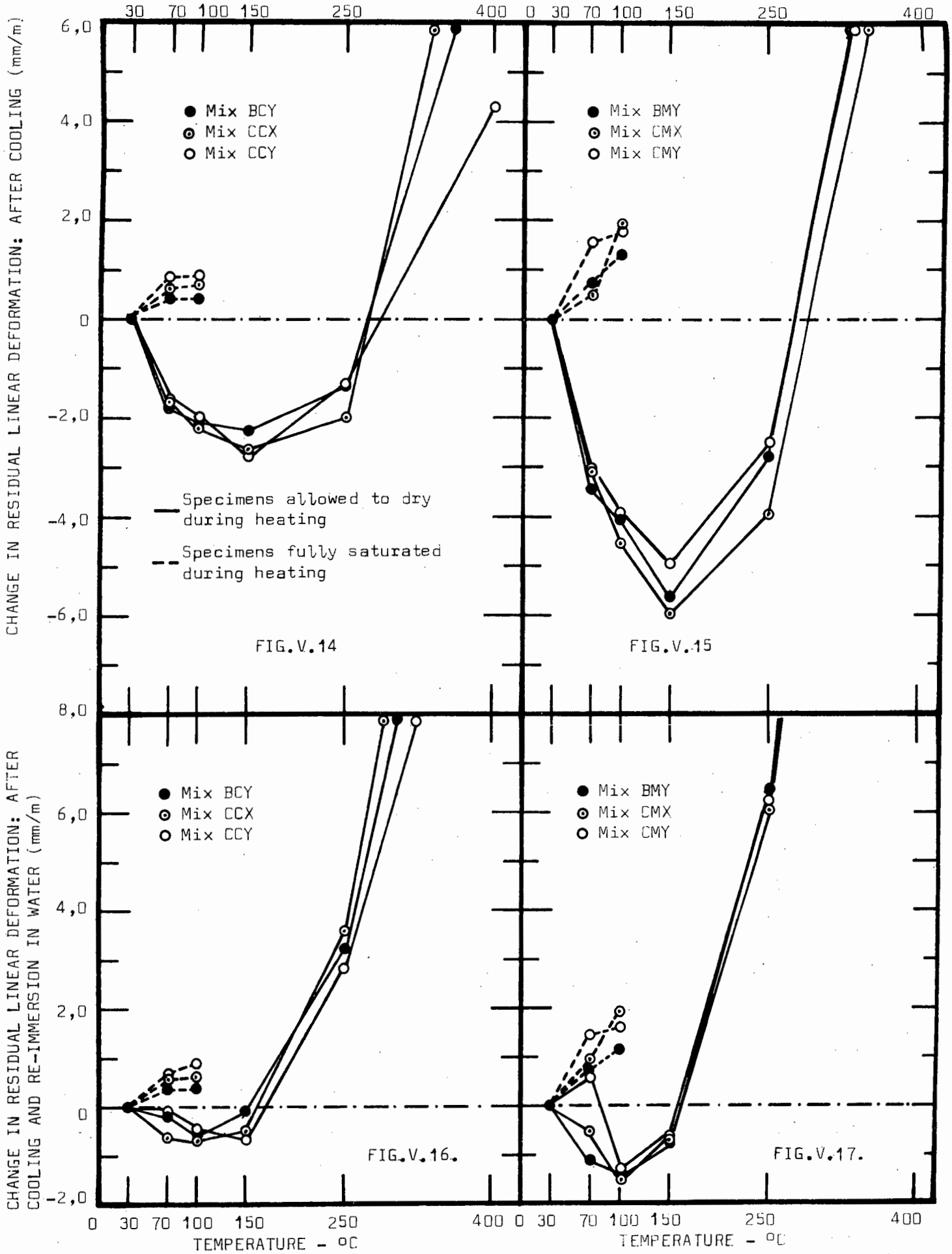

FIG.V.14 & FIG.V.16: The change in residual linear deformation of test specimens made from the three concrete mixes.

FIG.V.15 & FIG.V.17: The change in residual linear deformation of test specimens made from the three mortar mixes.

temperatures and re-immersed in water for 7 days before testing.

It is apparent from Figure V.14, Figure V.15, Figure V.16 and Figure V.17 that for test specimens which underwent drying at the various temperature levels the residual linear deformation of test specimens made from a particular concrete or mortar mix cannot be singled out as always being greater than, or less than, the residual deformation of any of the other concrete or mortar mixes. However, for test temperatures of 70°C, 100°C, 150°C and 250°C, the residual contraction of test specimens made from the mortar mix CMY is always less than the residual contraction of test specimens made from the mortar mixes BMY and CMX respectively. This is because the aggregate content of test specimens made from mix CMY was higher than that for specimens made from either mix BMY or mix CMX *. Also, the residual contraction of the mortar mix CMX is usually greater than the residual contraction of the mortar mixes BMY and CMY: the mortar mix CMX had the lowest aggregate content of the three mixes. For test specimens made from the corresponding concrete mixes the above trends are apparent only at test temperatures of 100°C and 250°C: the concrete mix CCX exhibits the greatest residual contraction and the mix CCY the lowest residual contraction.

The residual expansion of test specimens which remained fully saturated during heating is usually greatest for the concrete and mortar mixes having the highest aggregate cement ratio, i.e. mixes CCY and CMY respectively. The stress analysis reported by Hsu[48] indicates that the stresses arising from incompatible expansion of concrete constituents are greater for mixes having a high volumetric concentration of aggregate than for mixes having a low volumetric concentration of aggregate. The greater residual expansion of the mixes having a high concentration of aggregate may therefore indicate that test specimens made from these mixes underwent greater creep during the heating period ** than test specimens made from mixes having a lower volumetric concentration of aggregate. It should be remembered, though, that creep is also dependent on the volumetric concentration of aggregate; the lower the volumetric concentration of aggregate, the higher the cement paste content and subsequently the higher the creep[30]. This may partly explain why the residual expansion of the concrete and mortar mixes CCX and CMX respectively is always greater than the residual expansion of the corresponding concrete and mortar mixes BCY and BMY respectively, despite the fact that the former mixes have a lower volumetric concentration of aggregate than the latter mixes. However, it should be remembered that in CHAPTER 2 it was shown that neat cement paste also exhibits a residual expansion when cooled after heating

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* It is well known that an increase in aggregate content reduces the drying shrinkage of concrete[30].

** This aspect of the residual linear deformation was discussed in CHAPTER 2.

in the fully saturated state. This is a further explanation as to why the residual expansion of the mixes CCX and CMX (high cement paste content) is greater that the residual expansion of mixes BCY and BMY (low cement paste content).

It is interesting to compare the variation in the residual linear deformation data which results from testing specimens at successive test times with the variation which occurred as a result of having test specimens made from the different mixes. Almost without exception, the variation due to the time effect is greater than the variation between mixes. This illustrates once again the importance of heating time in experimental work of this nature.

3.4 Coefficient of thermal expansion

The data reported in PART III : CHAPTER 8 indicate beyond doubt that the coefficient of thermal expansion of concrete is a function of the temperature level. This is because;

(i) the coefficient of thermal expansion of the aggregate is dependent on temperature level, and

(ii) the residual deformation which occurs for both concrete and mortar test specimens is dependent on the test temperature.

The first of the abovementioned effects is adequately illustrated in PART I : LITERATURE REVIEW and also in PART III : EXPERIMENTAL RESULTS *. The second of the abovementioned effects becomes clear from the foregoing results of residual linear deformation. Particular attention is drawn to these effects since some investigators, notably Phillеo[29] and Harada[7] obtain the coefficient of thermal expansion of concrete by determining the slope of the linear deformation vs. temperature graph. It is apparent that the coefficient so obtained will not necessarily be correct.

Consider the data plotted in Figure V.18. In this diagram the linear expansion of test specimens made from the concrete mix BCY and the mortar mix BMY respectively is plotted against temperature level. The two sets of data exhibit similar trends. It appears from these graphs that above a temperature level of 150°C the coefficient of thermal expansion of both the concrete and the mortar test specimens increases, i.e. the slope of the line through either of the two sets of data increases above a temperature of 150°C. By determining the total linear deformation (per degree centigrade)

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* This refers to the coefficient of thermal expansion data for the aggregate used in the present investigation.

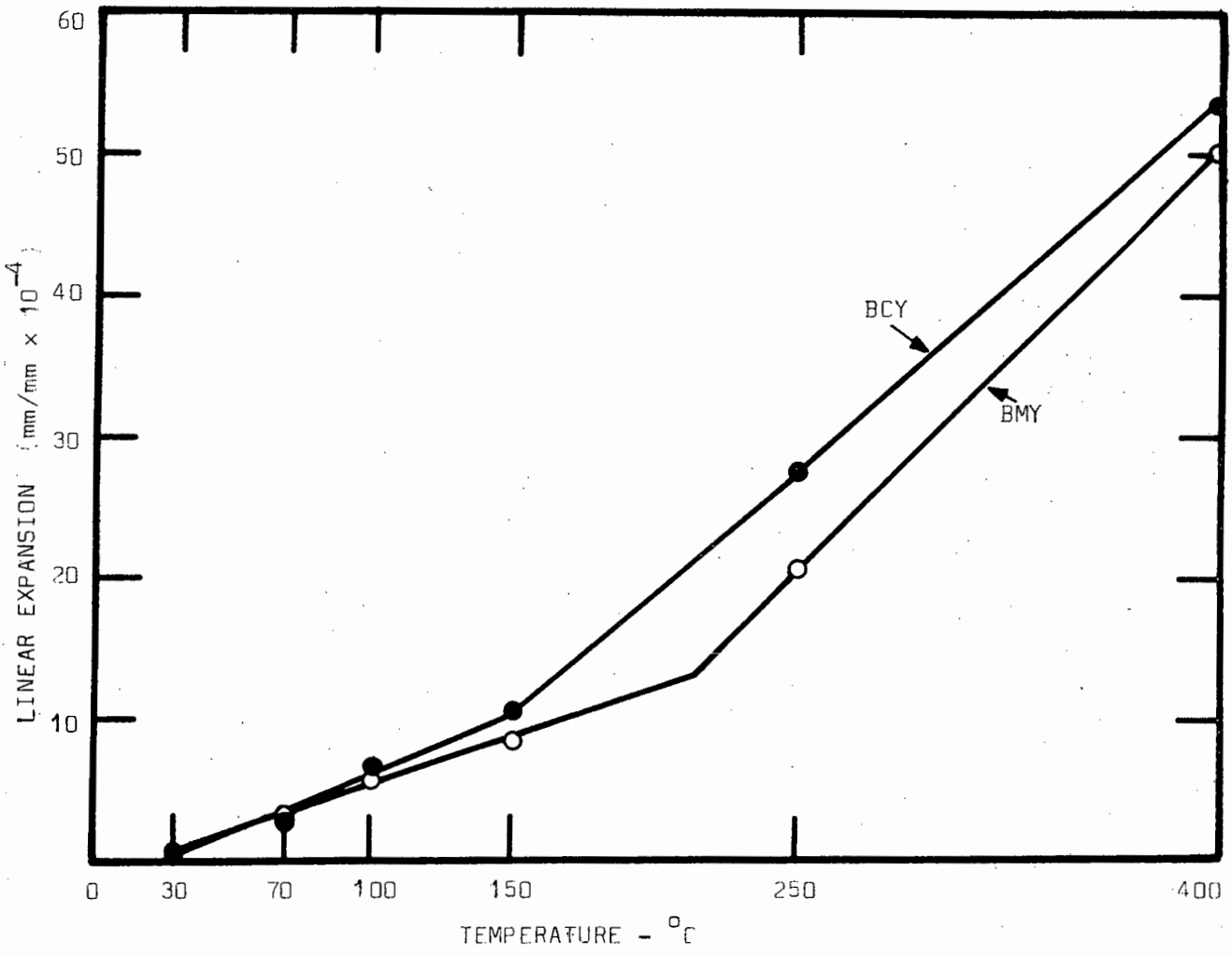

FIG.V.18: Values of linear expansion after approximately 40 hours heating, for test specimens made from the concrete mix BCY and the mortar mix BMY.

of test specimens upon cooling to the datum temperature, it is found that: *

(i) The coefficient of thermal expansion of the mortar test specimens is lower at temperatures of either 250°C or 400°C than at 150°C.

(ii) The coefficient of thermal expansion of the concrete specimens is higher at temperatures of either 250°C or 400°C than at 150°C.

The above example illustrates that the coefficient of thermal expansion of concrete should be determined only for a particular temperature level. This does not apply only to specimens which are allowed to dry during heating since permanent dilation also occurs in saturated test specimens at the relatively low temperatures of 70°C and 100°C. This permanent dilation should be taken into account when determining the coefficient of thermal expansion of a particular concrete or mortar.

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* These results are reported in PART III : CHAPTER 8.

CHAPTER 4 : COMPRESSIVE STRENGTH

4.1 Summary of Results

4.1.1 Specimens tested whilst hot

4.1.1.1 Drying during heating

The compressive strength of both mortar and concrete test specimens heated to temperatures of either 70°C or 100°C is usually reduced. The maximum reductions in compressive strength at these temperature levels are 15% and 25% respectively. At 150°C the compressive strength is usually higher than the compressive strength at either 70°C or 100°C. In some instances the compressive strength of specimens tested at 150°C is as much as 15% greater than the mean compressive strength of the control specimens. However, certain test specimens heated to 150°C do exhibit reductions in compressive strength; these reductions are not at large as the reduction in compressive strength which occurred at either 70°C or 100°C. At 250°C the compressive strength of test specimens is approximately the same as the compressive strength of corresponding specimens tested at 150°C for certain mixes, and lower than the compressive strength of corresponding specimens tested at 150°C for other mixes. The maximum reduction in compressive strength of specimens tested at 250°C is approximately 15%. Test specimens which were heated to 400°C always exhibit a reduction in compressive strength. The reductions are of the same order as those which occurred for test specimens heated to 100°C and ranged between 10% and 20%.

4.1.1.2 Specimens fully saturated until tested

The compressive strength of test specimens heated to either 70°C or 100°C is always reduced. The maximum reduction at 70°C is 20% and the maximum reduction at 100°C is 35% . At both 70°C and 100°C the respective reductions in compressive strength are greater than the reductions in compressive strength of test specimens which underwent drying at these temperature levels.

4.1.2 Specimens tested after slow cooling

4.1.2.1 Drying during heating

The compressive strength of specimens cooled from 70°C before testing is usually higher than the mean compressive strength of the control specimens. However, the increase in compressive strength is usually less than 10%. Also, for test specimens cooled from 70°C the compressive strength is higher that that of specimens tested whilst hot at 70°C. The compressive

strength of specimens cooled from 100°C before testing is always reduced. The reduction in compressive strength is usually smaller than 10% and is not as large as the reduction which occurred for the corresponding specimens tested whilst hot at 100°C. The compressive strength of test specimens cooled from 150°C before testing does not differ appreciably from the compressive strength of test specimens tested hot at 150°C. Some test specimens which were cooled from 150°C have a compressive strength which is as much as 15% higher than the mean compressive strength of control specimens. However, reductions in compressive strength were apparent for certain of the test specimens, but these reductions in strength were smaller than the reduction in strength of specimens cooled from 100°C.

Test specimens cooled from 250°C always exhibit a reduction in compressive strength of between 1% and 20%. The compressive strength of these test specimens is usually lower than the compressive strengths of specimens cooled from either 70°C, 100°C or 150°C. Furthermore, the compressive strength of specimens cooled from 250°C is always approximately 10% lower than the compressive strength of specimens tested whilst hot at 250°C. The largest reductions in compressive strength occurred for test specimens cooled from 400°C before testing; reductions of 40% are not uncommon. Specimens cooled from 400°C before testing exhibit up to 20% greater reductions in compressive strength than specimens which were tested hot at 400°C.

4.1.2.2 Specimens fully saturated until tested

Test specimens which remained fully saturated at 70°C and were cooled before testing usually exhibit a reduction in compressive strength. The maximum reduction in strength is 16% and, in general, the reductions in strength are not as great as those which occurred for specimens tested whilst hot. At 100°C the reductions in compressive strength are between 8% and 30%. For a particular mix, the reduction in compressive strength is always greater for specimens cooled from 100°C than for specimens cooled from 70°C. It is particularly apparent that saturated test specimens which were cooled from 100°C before testing exhibit less reduction in compressive strength than specimens tested whilst hot at 100°C. However, the difference between the respective reductions was usually less than 10%.

4.1.3 Specimens cooled and immersed in water for 7 days before testing

4.1.3.1 Drying during heating

The compressive strength of specimens which were cooled from temperatures of either 70°C, 100°C, 150°C, 250°C or 400°C and immersed in water for 7

days before testing, is always reduced. For test temperatures of 70°C and 100°C the maximum reductions are 15% and 25% respectively. The compressive strength does not differ appreciably between specimens cooled from the respective temperatures of 150°C, 250°C and 400°C and immersed in water for 7 days before testing. At these temperature levels the reduction in compressive strength is between 20% and 40%. At temperature levels of 70°C, 100°C, 150°C and 250°C the reductions in compressive strength are greater than the reductions in compressive strength which occurred for specimens tested whilst hot, and also greater than the reductions in compressive strength for specimens tested after cooling. Test specimens which were cooled from 400°C and immersed in water for 7 days prior to testing, exhibit reductions in compressive strength which are similar to the reductions for specimens that were tested after cooling from 400°C.

4.1.3.2 Specimens fully saturated until tested

The maximum reduction in compressive strength of saturated test specimens which were cooled and immersed in water for 7 days before testing is 12% at 70°C and 25% at 100°C. These reductions in compressive strength are approximately the same as those for;

(a) saturated specimens which were cooled before testing, and

(b) specimens which underwent drying at these temperature levels and were cooled and immersed in water for 7 days before testing.

4.2 The Effect of Heating Time

4.2.1 Specimens tested whilst hot

The effect of heating time on compressive strength is illustrated in Figure V.19 and Figure V.20. In Figure V.19 the mean coded values of compressive strength (i.e. the coded values obtained by averaging across the mixes) are illustrated for test specimens made from the concrete mixes. Figure V.20 shows the data obtained from test specimens made from the mortar mixes.

For a particular test temperature in each of Figure V.19 and Figure V.20, two mean coded values are given. These are the minimum mean coded value and the maximum mean coded value of compressive strength that were obtained from tests performed at the successive test times during the heating period. At certain of the test temperatures an arrow is drawn from the minimum value to the maximum value, or vice versa: this shows that the statistical analysis (reported in PART IV) indicates a significant trend between successive tests during the heating time at the particular

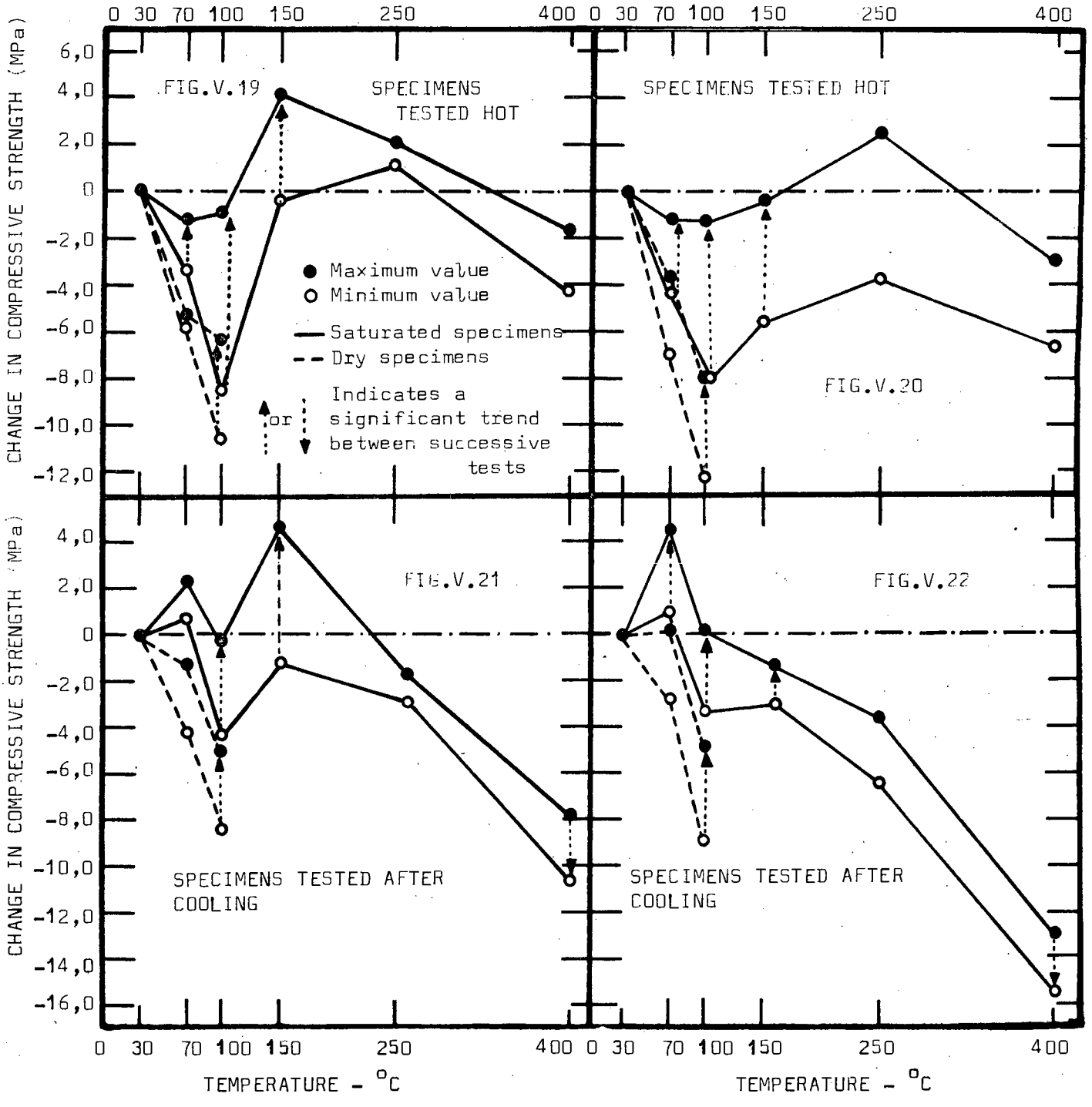

FIG.V.19 & FIG.V.21: The mean coded values of compressive strength for test specimens made from the concrete mixes

FIG.V.20 & FIG.V.22: The mean coded values of compressive strength for test specimens made from the mortar mixes.

temperature. The direction indicated by the arrow shows whether the compressive strength increases of decreases during the heating period.

Figure V.19 and Figure V.20 illustrate that the compressive strength of specimens tested whilst hot follows the general behaviour described in section 4.1. It is apparent also that the reductions in compressive strength of test specimens made from the mortar mixes are usually greater than, or equal to, the reductions in compressive strength of the concrete test specimens. This was verified statistically by the analysis reported in PART IV. Figure V.19 and Figure V.20 indicate, too, that for both concrete and mortar specimens which underwent drying at temperatures of either 70°C, 100°C or 150°C, and for specimens which remained fully saturated at 100°C, the compressive strength increases most significantly during the heating period. The initial reductions in compressive strength of specimens which underwent drying at temperatures of either 70°C, 100°C or 150°C are almost completely eliminated by the increase in compressive strength during the heating period: the reductions in compressive strength at the end of the heating period are usually less than 4%.

The greatest change in compressive strength during the heating period occurred for test specimens which underwent drying at 100°C. The change in compressive strength of test specimens at this temperature level was approximately 7 MPa. This corresponds to a percentage increase in strength * of approximately 15% for the concrete test specimens and 20% for the mortar test specimens. Despite the fact that test specimens heated to 150°C did not exhibit as large an increase in strength during the heating period as specimens heated to 100°C, the compressive strength of specimens heated to 150°C is greater than the compressive strength of specimens heated to 100°C. For concrete test specimens heated to 150°C, the compressive strength after the heating period is approximately 10% greater than the mean strength of unheated test specimens.

Test specimens which remained fully saturated at 100°C and were tested whilst hot, also exhibit an increase in compressive strength during the heating period. The increase in strength is approximately 4 MPa: this corresponds to a percentage increase in strength of approximately 8% for concrete test specimens and 12% for mortar specimens. However, this increase in compressive strength during the heating period only partially reduced the initial reduction in compressive strength and at the end of the heating period these specimens still exhibit an overall reduction in

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* As a percentage of the mean strength of unheated reference test specimens.

compressive strength. This reduction * in compressive strength is approximately 12% to 15% for concrete test specimens and 15% to 20% for mortar test specimens.

The compressive strength of both concrete and mortar test specimens which remained fully saturated at a temperature of 70°C, and test specimens which underwent drying at test temperatures of either 250°C or 400°C, does not exhibit a statistically significant increase with time during the heating period.

It is interesting to compute the slope of the line of best fit through the mean coded values of compressive strength as determined at each of the test temperatures. The line of best fit is obtained by a regression analysis of the mean coded values against time, i.e. the time axis is the independent variable and represents the successive tests that were performed at fixed intervals during the heating period **. Table V.1 illustrates the slope of the line of best fit through the mean coded values of compressive strength determined at the successive test times at a particular temperature.

TABLE V.1 : Regression coefficients from a linear regression of mean coded values of compressive strength at a particular temperature level : specimens tested whilst hot.

TEST TEMPERATURE	REGRESSION COEFFICIENT (MORTAR)	REGRESSION COEFFICIENT (CONCRETE)
70°C (SAT)	0,59	0,02
100°C (SAT)	1,59	1,11
70°C (DRY)	1,15	0,65
100°C (DRY)	2,08	2,40
150°C (DRY)	1,63	0,96
250°C (DRY)	0,10	0,43
400°C (DRY)	-0,76	0,33

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* As a percentage of the mean compressive strength of unheated reference test specimens.

** The regression analysis is discussed in PART IV : STATISTICAL ANALYSIS.

It is apparent that, for test specimens which underwent drying during heating, the regression coefficient is higher for specimens tested at 100°C than for specimens tested at 70°C. Also, at temperature levels above 100°C the regression coefficient decreases progressively as the temperature level increases. Thus the greatest increase in compressive strength during the heating period occurs for specimens which underwent drying at 100°C. At the temperature levels above 100°C the increase in compressive strength during the heating period becomes progressively smaller and in one instance - for mortar specimens heated to 400°C - the regression coefficient indicates that the compressive strength of test specimens decreases between successive tests during the heating period. However, it should be noted that the statistical analysis did not indicate a statistically significant decrease in compressive strength with time for the mortar test specimens heated to 400°C.

The regression coefficients in Table V.1 also indicate that for both concrete and mortar specimens which remained fully saturated at 100°C;

(i) the increase in compressive strength during the heating period is greater than the increase which occurred for specimens which remained fully saturated at 70°C, and

(ii) the increase in compressive strength during the heating period is not as great as the increase in compressive strength which occurred for specimens which underwent drying at 100°C.

4.2.2 Specimens tested after cooling

The effect of heating time on the compressive strength of specimens tested after cooling from the respective temperature levels is illustrated in Figure V.21 and Figure V.22. Figure V.21 shows the mean coded values of compressive strength for specimens made from the concrete mixes, and Figure V.22 the mean coded values for specimens made from the mortar mixes. The arrows drawn in Figure V.21 and Figure V.22 show that the statistical analysis (reported in PART IV) indicates a statistically significant trend between the tests performed at the successive times during the heating period. The direction indicated by the arrow in these diagrams shows whether the compressive strength increases or decreases during the heating period.

It is apparent from Figure V.21 and Figure V.22 that the compressive strength of both concrete and mortar test specimens which remained fully

saturated at 100°C increases by approximately 4 MPa during the heating period. This corresponds to a percentage increase in compressive strength of approximately 8% for concrete specimens and 12% for mortar test specimens. Although the increase in compressive strength of these test specimens is the same as the increase in compressive strength of saturated specimens which were tested hot at 100°C, it appears that the compressive strength of concrete and mortar specimens tested after cooling is always higher than the compressive strength of saturated specimens tested whilst hot. The difference in strength is in some instances as large as 8% but is usually between 2% and 6%. Specimens which remained saturated at 70°C and were cooled before testing do not exhibit an increase in compressive strength during the heating period. However, it is again apparent that the compressive strength after cooling is greater than the compressive strength of specimens tested hot.

Concrete and mortar test specimens which underwent drying at temperatures of either 100°C or 150°C and were cooled before testing exhibit an increase in compressive strength for tests performed at the successive test times during the heating period. The increase in compressive strength is usually not as great as the increase which occurred for specimens tested whilst hot. However, the compressive strength of these specimens is always higher than the compressive strength of specimens which underwent drying at either 100°C or 150°C and were tested whilst hot.

Mortar test specimens which underwent drying at 70°C and were tested after cooling exhibit an increase in strength during the heating period, whereas the test specimens made from the concrete mixes do not indicate a similar trend. For both concrete and mortar specimens, however, the compressive strength after cooling from 70°C is always greater than the mean compressive strength of unheated reference specimens.

The compressive strength of specimens which were tested after cooling from either 250°C or 400°C is always lower than the compressive strength of specimens tested hot at either 250°C or 400°C. The difference in compressive strength for specimens cooled from 250°C is approximately 10% for concrete specimens and between 5% and 15% for mortar specimens. For cooling from 400°C the difference in compressive strength is between 10% and 15% for concrete specimens and approximately 25% for mortar specimens. Furthermore, for specimens cooled from 400°C the compressive strength of both concrete and mortar specimens decreases for tests performed at successive times during the heating period. This reduction in strength is between 2 MPa and 3 MPa, and corresponds to a percentage reduction in strength of

of between 4% and 8% of the unheated reference strength.

The abovementioned differences between the compressive strength of specimens tested whilst hot and specimens tested after cooling are illustrated in Figure V.23. In Figure V.23 the mean coded values of compressive strength determined from specimens tested whilst hot is plotted against the mean coded value of compressive strength measured after specimens had cooled to the datum temperature. It is apparent that the data for either concrete or mortar specimens fall into two categories, viz:

(i) Test specimens which were tested at either 70°C (saturated), 100°C (saturated), 70°C (dry), 100°C (dry) or 150°C (dry). In these instances the best line * indicates that for both concrete and mortar test specimens the compressive strength of specimens tested after cooling is always greater than the compressive strength of specimens tested whilst hot.

(ii) Test specimens which underwent drying at either 250°C or 400°C. For these test temperatures the regression line * indicates that the compressive strength of both concrete and mortar specimens after cooling is always <u>lower</u> than the compressive strength of specimens tested whilst hot.

It is thought that the above results show whether or not microcracking occurs in test specimens subjected to heating. For test temperatures of 150°C and below, the fact that:

(i) the compressive strength increases with time during the heating period, and

(ii) the compressive strength of specimens after cooling is always higher than the compressive strength of specimens tested hot,

is thought to indicate that at these temperature levels microcracking does not have any significant influence on the compressive strength, i.e. for concrete and mortar specimens at temperature levels of either 70°C (fully saturated), 100°C (fully saturated), 70°C (dry), 100°C (dry) or 150°C (dry) the stresses which occur as a result of incompatible differential movement between the mix constituents are relieved by creep and not by microcracking.

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* This was determined by linear regression analysis. The equation of the best line is not given since the main objective is to illustrate qualitatively the difference between the abovementioned two categories.

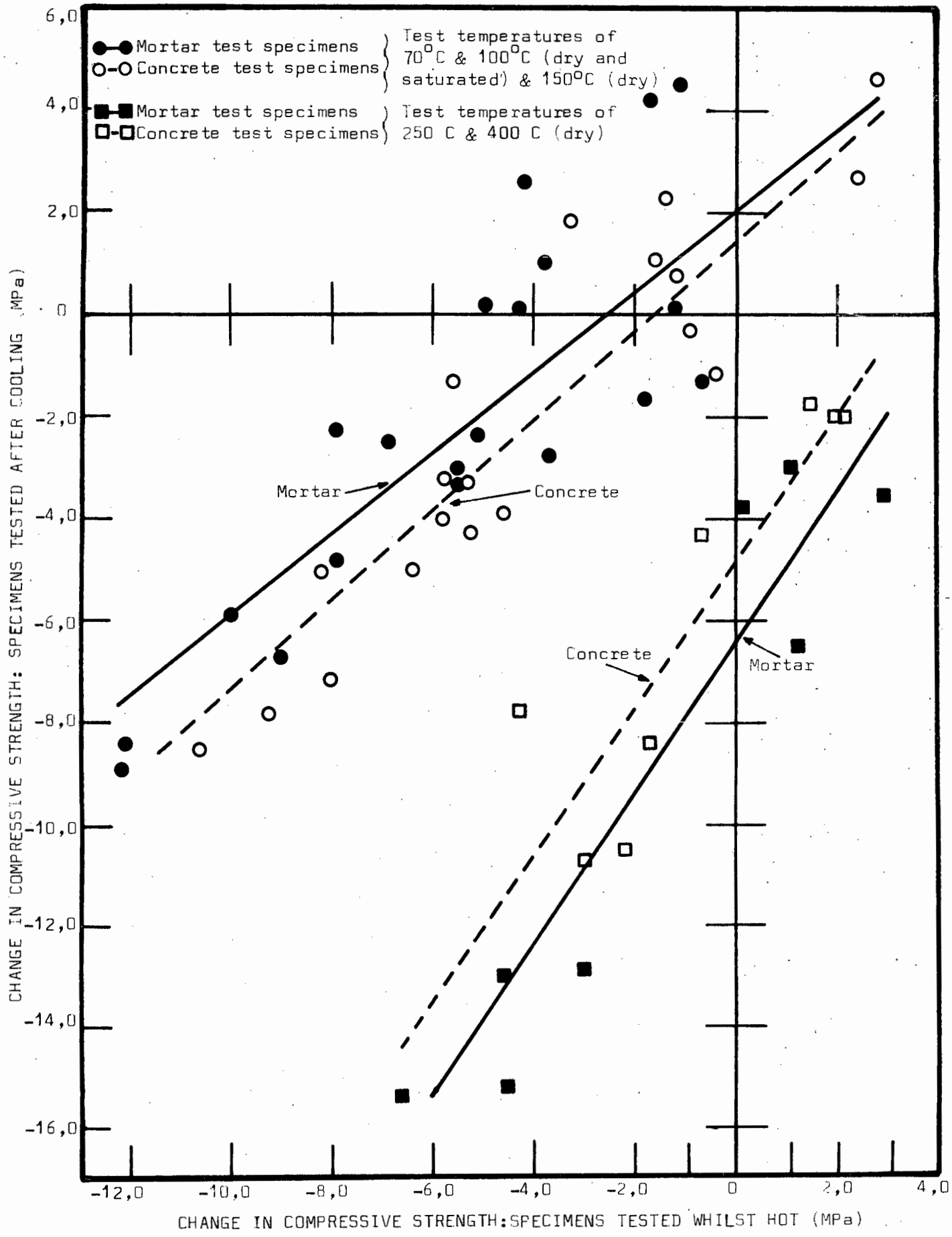

FIG.V.23: The relationship between the compressive strength determined whilst hot and the compressive strength determined after cooling.

In this regard numerous authors have indicated that creep, and also the rate of creep, of concrete is higher at elevated temperature than at room temperature. The relief of the stresses caused by incompatible differential expansion, therefore, partly explains the increase in compressive strength of saturated specimens heated to 100°C. However, in PART V : CHAPTER 2 it was shown that, during the heating period, time dependent chemical reactions may also occur within the cement paste. Work by Imlach[89] shows that the compressive strength of neat cement paste is reduced by approximately 50% under saturated steam conditions at 140°C. The reduction in strength is associated with the formation of α - C_2S hydrate. Imlach[89] further indicates that in the presence of siliceous aggregate a strength conferring reaction occurred under steam curing conditions and that all test specimens containing siliceous aggregate exhibited an increase in compressive strength. It was found that this reaction between cement paste and siliceous material also occurs within specimens heated under saturated conditions at 95°C, but to a lesser extent[89]. The increase in strength is associated with the formation of 11.3 Å tobermorite, $C_5S_6H_5$. Similar results are reported by Kalousek[90]. This author[90] found that the formation of the α - C_2S hydrate is unfavourable to strength and that the presence of siliceous aggregate favours the formation of the 11.3 Å tobermorite with a resulting increase in strength.

In the present investigation it is therefore highly probable that the above-mentioned chemical reactions occurred for test specimens heated to 100°C under saturated conditions, particularly the reaction concerning siliceous aggregates since both the coarse and the fine aggregate used in this investigation has an SiO_2 content * of approximately 75%. This chemical reaction could also have occurred within test specimens heated to 70°C; Imlach[89] reports that even at temperatures as low as 25°C there is evidence of the reaction between cement paste and siliceous aggregate. However, it is likely that at 70°C the extent of the reaction during the heating period was not sufficient to have been apparent as an increase in compressive strength. It appears, therefore, that for concrete and mortar specimens which remained saturated at either 70°C or 100°C the compressive strength and the linear expansion ** of specimens increase during the heating period as a result of the formation of 11.3 Å tobermorite. The increase in linear expansion of neat cement paste specimens which remained fully saturated at either 70°C or 100°C is probably associated with the formation of α - C_2S hydrate. It is interesting with regard to the chemical reactions to note some further findings by Imlach[89]. The author

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* This is reported in PART II.

** See CHAPTER 2.

reports data which indicate that by using only limestone aggregate, the formation of the weaker $\alpha - C_2S$ hydrate is not prevented and no 11.3 Å tobermorite is formed. Test specimens made with limestone aggregate exhibit a 50% reduction in compressive strength when heated under saturated steam conditions at 100°C[89].

It is likely that the formation of 11.3 Å tobermorite also contributes to the increase in strength of specimens which underwent drying at test temperatures of either 70°C or 100°C. At these temperature levels the migration of evaporable water is a relatively slow process. (This is shown in PART III.) Consequently, sufficient water would be present for the above reaction to occur. However, it is thought that for specimens which underwent drying at either 70°C, 100°C or 150°C, the increase in compressive strength during the heating period was primarily due to the loss of adsorbed intercrystalline water from between the gel crystallites. This results in a small distance between gel crystals and thus causes an increase in the van der Waals forces. Consequently, the compressive strength increases. Also, new chemical bonds (i.e. solid-solid bonds) may occur in instances where the distance between gel crystals is reduced to zero.

It may be argued that the loss of the strongly adsorbed intercrystalline water only occurs after all the more loosely held evaporable water has been driven off, and consequently this effect would not be significant at the relatively low temperatures of 70°C or 100°C. However, it should be remembered that the loss of water from capillary pores and gel pores subjects the solid system to isotropic elastic shrinkage, i.e. the reduction of the menisci radii in the gel pores and capillary pores increases the tensile forces in the water and causes corresponding elastic contraction of the solid. Ishai[34] indicates that under the action of this hydrostatic compressive stress the adorbed confined water, i.e. the water between gel crystals, squeezes out slowly and reduces the small inter-solid gaps. The author[34] likens this process to the irrecoverable creep mechanism under an external load.

It is thought that apart from the abovementioned hydrostatic creep affect as evaporable water is lost from the cement paste at temperatures of 70°C, 100°C and 150°C, further creep occurs in order to relieve the stresses which occur as a result of cement paste contraction relative to aggregate particles. In PART I : CHAPTER 4 it is shown that the tensile stresses which may occur when cement paste undergoes contraction relative to aggregate particles are many times greater than the ultimate tensile stress

normally associated with either mortar or cement paste. (It should be noted that this effect is independent of the aggregate expansion). The fact that at temperatures below 150°C the compressive strength of test specimens increases during the heating period despite the fact that the contraction of cement paste relative to aggregate particles also increases during the heating period, is thought to indicate that these stresses were relieved by creep.

It should be remembered, however, that for test specimens which underwent drying at temperatures below 150°C a further effect may have occurred. This is the dissolution of crystals of $Ca(OH)_2$ as a result of the compressive stress imposed by drying shrinkage and resulting in precipitation of either $CaCO_3$ or $Ca(OH)_2$ in spaces free from stress *. The compressibility of the cement paste may thus be increased. The abovementioned effect may not necessarily be detrimental to the compressive strength since the $Ca(OH)_2$ does not contribute significantly to the strength of cement paste. Furthermore, if $CaCO_3$ is precipitated, the compressive strength may increase[51]. The increase in compressibility of the paste may be apparent as a reduction in Young's modulus. This is discussed in CHAPTER 5.

The foregoing results indicate that for test specimens which underwent drying at 400°C;

(i) the compressive strength of specimens after cooling is lower than the compressive strength of specimens tested whilst hot, and

(ii) the compressive strength decreases for specimens cooled and tested at the successive test times during the heating period.

It is thought that these results indicate conclusively that microcracking has a significant influence on the property behaviour of test specimens heated to 400°C. This is further substantiated by the results of water loss (after cooling and re-immersion in water) and residual linear deformation data of specimens cooled from this temperature level **. Despite the fact that test specimens which were heated to 250°C exhibit only the first of the abovementioned behavioural patterns but not the second, it is thought that these test specimens fall into the same category as

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* There will be a tendency to precipitate $CaCO_3$ if carbonic species are present in the water. This is because solubility of $CaCO_3$ is much lower than the solubility of $Ca(OH)_2$. However, it is difficult to assess whether diffusion of CO_2 into capillary and gel water could have occurred in the relative short time period when test specimens underwent water loss.

** These results were discussed in CHAPTER 1 and CHAPTER 3 respectively.

specimens heated to 400°C. The results of water loss (after cooling from 250°C and re-immersion in water) and residual linear deformation of specimens cooled from 250°C substantiate this conclusion.

At test temperatures of 250°C and 400°C the water loss data indicate that all the eveporable water is removed. Consequently, it appears that because the intercrystalline water is not present, the micro-structure of the paste is fixed by predominantly solid-solid bonding between gel crystallites. Since the cement paste may no longer be considered as mobile, the stresses which arise from either;

(i) contraction of the paste relative to aggregate as a result of the loss of non-evaporable water, or

(ii) the difference between the coefficient of thermal expansion of cement paste and aggregate (during cooling of specimens),

are not therefore relieved by creep. It is likely that these stresses are of sufficiently great magnitude to cause microcracking within the paste. This was shown in PART I : CHAPTER 4 and also PART V : CHAPTER 2.

If microcracking does not occur at test temperatures of either 250°C or 400°C, the compressive strength of test specimens may increase due to the loss of evaporable water and subsequent increase in the van der Waals forces. However, this cannot be stated with certainty since a further effect may tend to decrease the strength. This is the loss of non-evaporable water from tobermorite gel, ($C_3S_2H_3$, or more correctly, $C_{1,62}\ S\ H_{1,5}$). The dehydration residue of tobermorite gel consists[86] mainly of β - C S (hillebrandite). Little is known about the relative strength of the tobermorite and the dehydration residue. However, it does seem likely that the strength of the paste is reduced when dehydration of tobermorite occurs.

It should be noted that at temperatures of 250°C and 400°C there will be no tendency for dissolution of $Ca(OH)_2$ under the compressive strength imposed by drying shrinkage as for specimens heated to either 70°C or 100°C. This is because complete loss of evaporable water at these test temperatures occurs during the time period when test specimens are being heated to the desired temperature level. Also, at 400°C the dehydration of $Ca(OH)_2$ may have occurred. However, in CHAPTER 2 it is shown that this effect is probably not significant at 400°C.

4.2.3 Specimens tested after cooling and 7 days re-immersion in water

Figure V.24 illustrates the effect of heating time on the compressive strength of concrete test specimens which were cooled at successive test times during the heating period and immersed in water for 7 days before testing. Figure V.25 shows the compressive strength data for test specimens made from the mortar mixes and tested as explained above.

For each test temperature in Figure V.24 and Figure V.25, two mean coded values of compressive strength are shown. These are the maximum and minimum mean coded values which were obtained from compressive strength from tests on specimens that were cooled at the successive test times during the heating period. At certain of the test temperatures an arrow is drawn between the maximum and minimum mean coded value, or vice versa: this shows that the statistical analysis (reported in PART IV) indicates a statistically significant trend between the successive tests performed during the heating time at the particular temperature. The direction indicated by the arrow shows whether an increase or a reduction of compressive strength occurred.

It is apparent from Figure V.24 and Figure V.25 that the compressive strength of specimens which were tested after cooling and re-immersion in water, follows the general behaviour described in section 4.1. The data also shows that the reduction in compressive strength of test specimens made from the mortar mixes is usually either greater than or equal to the reduction in compressive strength of concrete test specimens. This was verified statistically by the analysis reported in PART IV.

The compressive strength of test specimens which remained fully saturated at temperatures of either 70°C or 100°C and were stored in water for 7 days after cooling is always higher than the compressive strength of specimens tested immediately after cooling. This is probably due to additional hydration during the 7 day immersion period.

Figure V.24 and Figure V.25 also indicate that the compressive strength of test specimens which underwent drying at test temperatures of either 70°C, 100°C or 150°C and were immersed in water for 7 days after cooling, is always lower than the compressive strength of specimens which were tested immediately after cooling. Furthermore, the coded values of compressive strength for specimens which were cooled from these temperatures and re-immersed in water at the various test times during the heating period indicate a most significant trend: for both concrete and mortar specimens

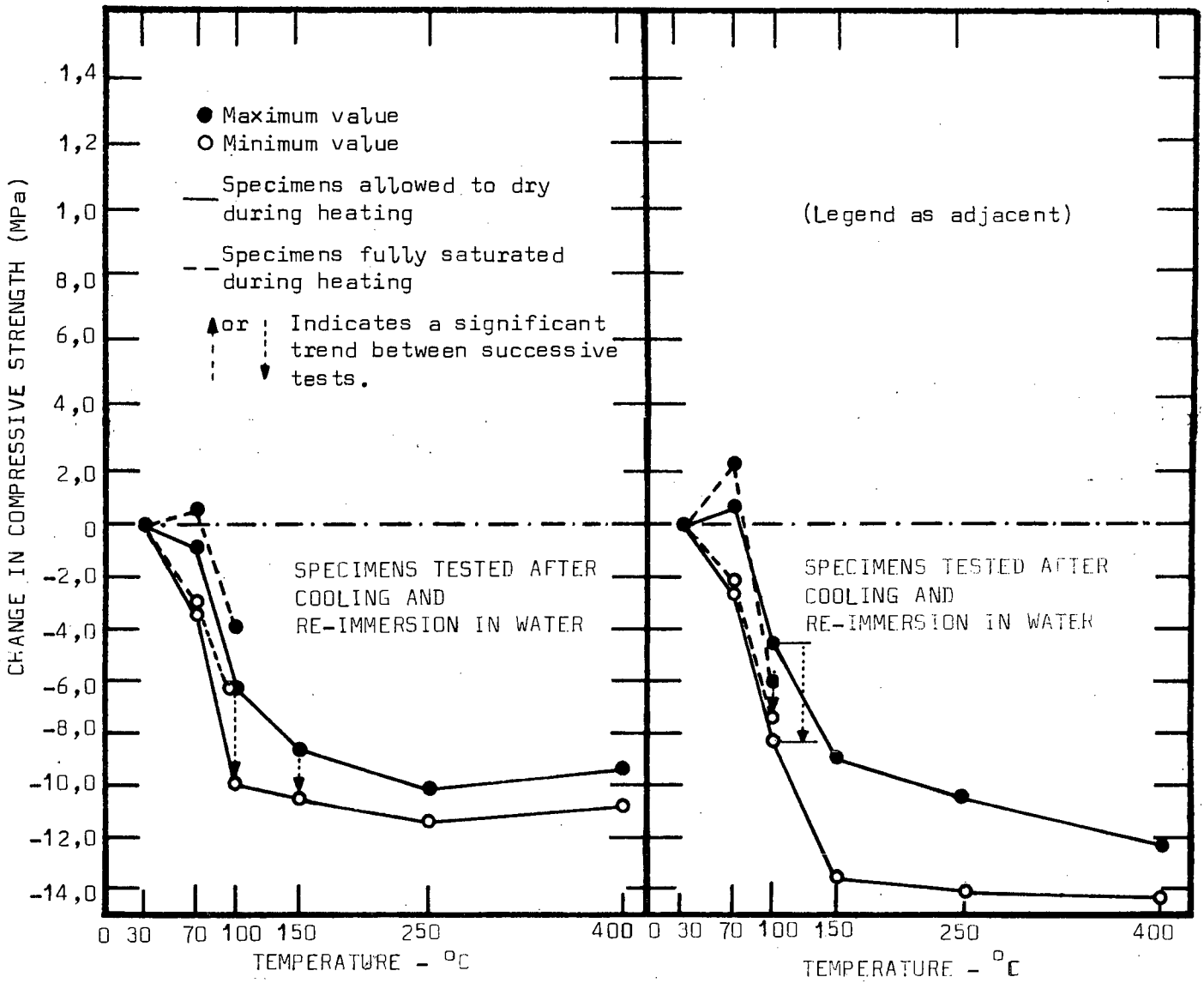

FIG.V.24: The mean coded values of compressive strength for test specimens made from the concrete mixes.

FIG.V.25: The mean coded values of compressive strength for test specimens made from the mortar mixes.

the compressive strength decreases for tests performed at the successive test times during the heating period. In this regard it should be remembered that the compressive strength of specimens which were tested immediately after cooling from either 70°C, 100°C or 150°C exhibited exactly the opposite trend, i.e. the compressive strength increased for specimens cooled and tested at the successive test times during the heating period.

It is thought that the abovementioned reduction in the compressive strength of test specimens is related to the irrecoverable shrinkage deformation of the cement paste during the heating period. The irrecoverable shrinkage deformation occurs as a result of the loss of intercrystalline adsorbed water and intercrystalline (zeolitic) water. If the test temperature is sufficiently high, the intercrystalline and intracrystalline water is removed and new chemical or physical bonds are formed between solid elements. Also, at relatively low temperature levels the intercrystalline water may squeeze out slowly under the prolonged hydrostatic compressives stresses * induced by surface tension in the liquid phase as evaporable water is lost from the capillary and gel pores. Consequently, when test specimens are re-immersed in water, the water molecules cannot re-occupy the now closed original spaces, i.e. tensile stresses are induced in the newly formed inter-solid bonds.

Furthermore, upon re-immersion the cement paste swells relative to aggregate particles. In PART I : CHAPTER 4 it was shown that the tensile stresses which may result from a contraction of cement paste relative to aggregate are higher than the tensile stresses which cement paste, or mortar, can withstand. It was also shown that the tensile stresses resulting from an expansion of paste relative to aggregate are many times higher than the stresses resulting from paste contraction relative to aggregate[48]. Consequently, it is likely that the swelling of the paste relative to aggregate particles causes large tensile stresses either within the paste or at the paste aggregate interface. These stresses will be relieved by creep. However, it must be remembered that both creep, and creep rate, are lower at room temperature than at the temperature at which the contraction of paste relative to aggregate originally occurred.

It is thought, therefore, that tensile stresses in the solid phase causes the reduction in compressive strength of test specimens re-immersed in water. It is possible that these tensile stresses result in microcracking within test specimens. However, this is not a necessary condition for a reduction in the compressive strength. Under a uniaxial compressive

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* This aspect was discussed in section 4.2.2.

stress the limiting value of tensile strain in the lateral direction is exceeded more quickly for test specimens having tensile stress in the solid phase than for specimens in which no tensile stress is present. Consequently, the test specimens fail at a lower value of uniaxial compressive stress.

Figure V.24 and Figure V.25 also show that the compressive strength of test specimens which were immersed in water for 7 days after cooling from 250°C is lower than the compressive strength of specimens tested immediately after cooling from 250°C (refer Figure V.21 and Figure V.22). In CHAPTER 3 : section 3.2.2 and CHAPTER 4 : section 4.2.2 it was concluded that micro-cracking occurs within the test specimens which were cooled from 250°C. When these test specimens are re-immersed in water the decrease in surface energy of the crack (due to adsorption of water on the surface of the crack) results in an increase in the crack length[87]. It is likely, too, that in certain instances the critical crack size was exceeded and that spontaneous propagation of some of the cracks occurred. Consequently, the compressive strength of re-immersed test specimens is lower than the compressive strength of specimens tested immediately after cooling from 250°C.

Comparing Figure V.24 and Figure V.25 to Figure V.21 and Figure V.22 respectively, it is apparent that for test specimens cooled from 400°C, the compressive strength of re-immersed test specimens is the same as the compressive strength of specimens tested immediately after cooling. This is thought to indicate that the extent of microcracking after cooling was of such severity that the additional microcracking which occurred when test specimens were re-immersed in water did not affect the compressive strength.

For test specimens cooled from either 250°C or 400°C and re-immersed in water, it is possible that some rehydration of dehydrated hydration products occurred. However, little is known about the strength of either the dehydration product (β - C S) or whether rehydration would result in the formation of tobermorite gel ($C_{1,62}\ S\ H_{1,5}$).

Lastly, it is interesting to note from Figure V.24 and Figure V.25 that the compressive strength of specimens cooled from either 100°C or 150°C and immersed in water before testing, usually decreases to a value which is approximately the same as the compressive strength of specimens immersed in water after cooling from either 250°C or 400°C. This is thought to be indicative of the high tensile stresses within test specimens which were cooled from either 100°C or 150°C and immersed in water before testing, i.e. on application of a uniaxial compressive stress the load required to produce spontaneous propagation of a crack is not much higher than the load required to fail a pre-cracked test specimen.

4.3 Comparison of the Compressive Strength of the Various Concrete Mixes and Mortar Mixes

The mean coded values of compressive strength (determined whilst hot) are shown in Figure V.26 for test specimens made from the three concrete mixes BCY, CCX and CCY respectively. Figure V.27 illustrates the data for the three mortar mixes BMY, CMX and CMY respectively. The mean coded value of compressive strength is the mean of the four coded values determined from the compressive strength tests which were performed at the successive times during the heating period. Figure V.28 and Figure V.29 illustrate the mean coded values of compressive strength for test specimens made from the various concrete or mortar mixes, respectively, and cooled before testing. The data for test specimens which were cooled and re-immersed in water for 7 days before testing are shown in Figure V.30 and Figure V.31.

The stress analysis by Hsu[48] indicates that the stresses which occur as a result of differential expansion of the constituents in concrete or mortar, are greater for specimens containing a high concentration of aggregate than for specimens containing a low concentration of aggregate. It is not unreasonable to expect that this may be reflected in the compressive strength of test specimens, particularly at the test temperatures at which unstable microcracking is thought to occur, viz. 250°C and 400°C. However, the compressive strength data shown in Figure V.26 to Figure V.30 do not indicate that the reduction in compressive strength of test specimens made from the concrete or mortar mixes having a high concentration of aggregate (mixes CCY and CMY) is always greater than the reduction in compressive strength of test specimens made from the concrete or mortar mixes having a low concentration of aggregate (mixes CCX and CMY respectively). This is probably because the difference between volumetric concentration of the aggregate in these mixes was not sufficiently great. It should be noted, though, that the change in volumetric concentration of aggregate was the maximum one possible within the limits of practibility, i.e. the $^{w}/_{c}$ ratio of the two mixes remained constant and thus the workability governed the increase in aggregate concentration.

Figure V.26 to Figure V.30 show that for concrete and mortar test specimens made from the mixes BCY and BMY respectively, and tested

(i) after cooling from temperatures of either 150°C, 250°C or 400°C, and

(ii) after cooling from temperatures of either 150°C, 250°C or 400°C, and 7 days re-immersion in water,

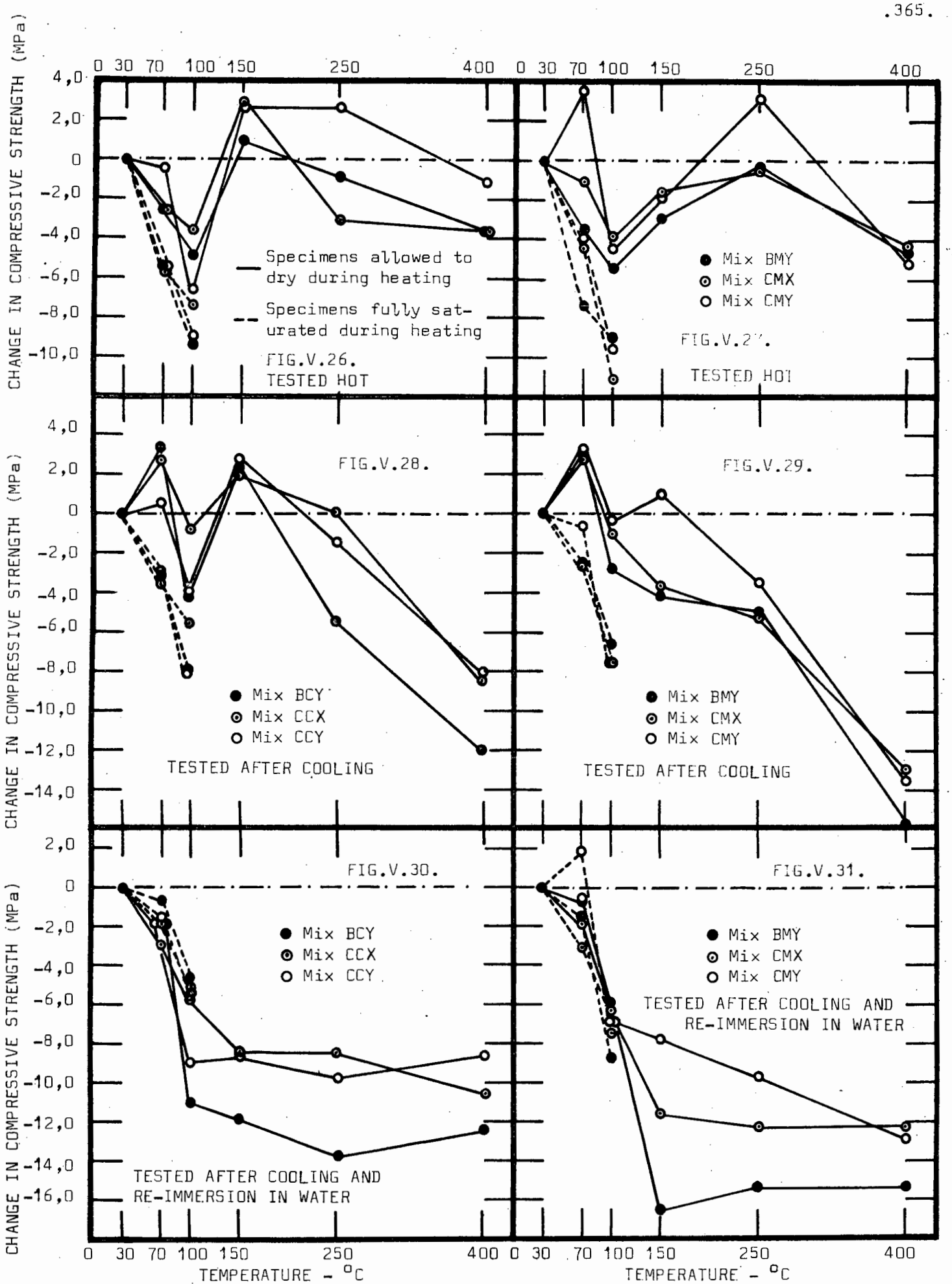

FIG.V.26.,FIG.V.28. & FIG.V.30 : The mean change in compressive strength of test specimens made from the three three concrete mixes.

FIG.V.27.,FIG.V.29. & FIG.V.31 : The mean change in compressive strength of test specimens made from the three mortar mixes.

the reduction in compressive strength is greater than the reduction in compressive strength of test specimens made from the other concrete or mortar mixes. This may indicate that the $^{w}/_{c}$ ratio does have an effect on the reductions in compressive strength of concrete and mortar specimens heated to these test temperatures: the $^{w}/_{c}$ ratio of mixes BCY and BMY was 0,50 whereas the $^{w}/_{c}$ ratio of all the other mixes was 0,58. This conclusion does not agree with data reported by Saeman and Washa[68]: the authors found no significant differences in the relative changes of compressive strength for concretes having $^{w}/_{c}$ ratios which ranged from 0,48 to 0,84. However, Furumura[70] reports results which indicate that low strength concrete exhibits overall smaller reductions in compressive strength at elevated temperatures than concrete of high strength. In the absence of any conclusive trends as regards the influence of either the aggregate content or the water content on the behaviour of concrete at elevated temperature, it is concluded that this part of the investigation was unsuccessful.

It is interesting to compare Figures V.26, V.27, V.28, V.29, V.30 and V.31 to Figures V.19, V.20, V.21, V.22, V.24 and V.25 respectively. From these diagrams it is apparent that in many instances the variation which results from performing tests at successive times during the heating period is greater than the variation which results from having test specimens made with different mix proportions. This again emphasises the importance of heating time in experimental work of this nature.

CHAPTER 5 : DYNAMIC YOUNG'S MODULUS

5.1 Summary of Results

5.1.1 Specimens tested after cooling

The dynamic Young's modulus is always reduced when concrete or mortar test specimens are heated. In general, the higher the temperature the greater the reduction in dynamic Young's modulus. The maximum percentage reductions in dynamic Young's modulus for specimens which underwent drying during heating were approximately:

18% for concrete test specimens and 16% for mortar test specimens at 70°C;
28% " " " " " 20% " " " " " 100°C;
28% " " " " " 38% " " " " " 150°C;
56% " " " " " 55% " " " " " 250°C;
90% " " " " " 85% " " " " " 400°C;

The maximum percentage reductions in dynamic Young's modulus for specimens which remained fully saturated at either 70°C or 100°C were between:

5% and 10% for concrete test specimens at 70°C;
2% " 10% " mortar " " " 70°C;
10% " 20% " concrete " " " 100°C;
10% " 24% " mortar " " " 100°C;

5.1.2 Specimens tested after 7 days re-immersion in water

The maximum percentage reduction in dynamic Young's modulus for concrete and mortar test specimens which were cooled and re-immersed in water after testing is approximately 20%. In some instances both concrete and mortar test specimens exhibit an increase in dynamic Young's modulus, i.e. an increase with respect to the dynamic Young's modulus of control specimens. However, the increase in dynamic Young's modulus is usually less than 5%.

Test specimens which were re-immersed in water after drying at a temperature of 70°C exhibit values of dynamic Young's modulus which are approximately the same as, or up to 10% greater than, the values for test specimens which were tested immediately after cooling from 70°C. Test specimens which underwent drying at temperatures of either 100°C, 150°C, 250°C or 400°C and were re-immersed in water after cooling, always exhibit a reduction in dynamic Young's modulus. The maximum reduction in dynamic Young's modulus for test temperatures of 100°C and 150°C were:

18% for concrete test specimens and 17% for mortar test specimens at 100°C;
20% " " " " " 33% " " " " " 150°C;

These reductions are between 5% and 10% smaller than the reductions in Young's modulus of test specimens which were tested immediately after cooling from either 100°C or 150°C. For test temperatures of 250°C and 400°C the maximum reductions in dynamic Young's modulus were:

20% for concrete test specimens and 32% for mortar test specimens at 250°C;
35% " " " " " 37% " " " " " 400°C.

At a test temperature of 250°C the reduction in dynamic Young's modulus of specimens which were re-immersed in water are between 25% and 40% less than the reductions for specimens which were tested immediately after cooling. The reduction in dynamic Young's modulus of specimens which were re-immersed in water after cooling from 400°C is approximately 50% smaller than the corresponding reduction of specimens which were tested immediately after cooling.

Concrete and mortar test specimens which remained fully saturated during heating and were cooled from 70°C and re-immersed in water, exhibit reductions in dynamic Young's modulus which are usually not greater than 10%. For specimens cooled from 100°C the reductions in dynamic Young's modulus for saturated concrete and mortar specimens are between 10% and 25%. At both 70°C and 100°C the reductions in dynamic Young's modulus of saturated specimens which were cooled and re-immersed in water are not as large as the reductions which occurred for saturated specimens which were tested immediately after cooling.

5.2 The Effect of Heating Time

5.2.1 Specimens tested after cooling

The effect of heating time on the dynamic Young's modulus of specimens tested immediately after cooling is illustrated in Figure V.32 and Figure V.33. Figure V.32 shows the mean coded values of dynamic Young's modulus for test specimens made from the concrete mixes * and Figure V.33 the data for test specimens made from the mortar mixes.

For a particular test temperature in each of Figure V.32 and Figure V.33, two mean coded values are given. These are the maximum mean coded value and the minimum mean coded value of dynamic Young's modulus that were

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* The mean of the coded values of dynamic Young's modulus for the three concrete mixes.

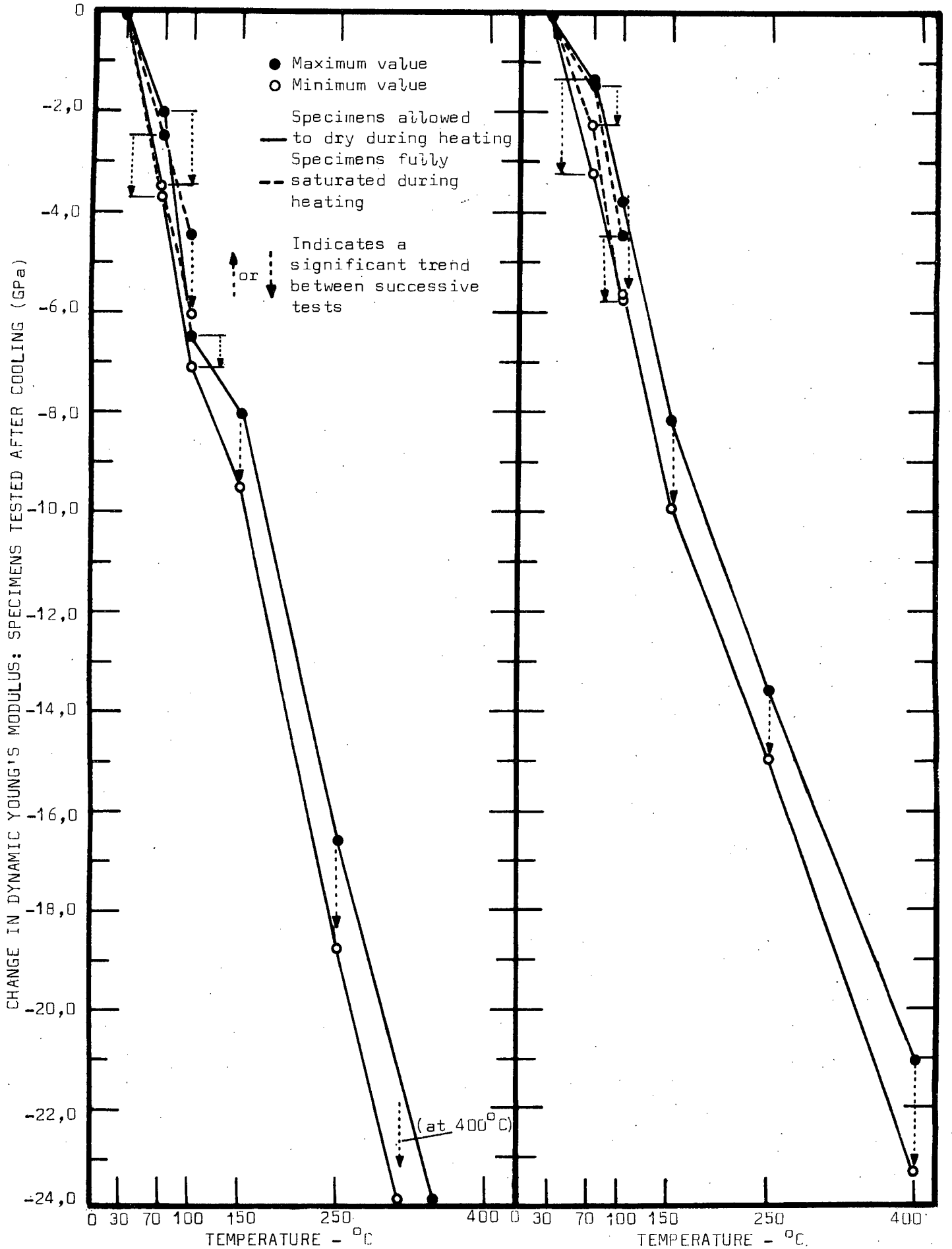

FIG.V.32: The mean change in dynamic Young's modulus for test specimens made from the concrete mixes.

FIG.V.33: The mean change in dynamic Young's modulus for test specimens made from the mortar mixes.

obtained from tests performed at the successive test times during the heating period. The arrow drawn between the minimum and maximum value, or vice versa, shows that the statistical analys indicates a significant trend between the successive tests at a particular test temperature. The direction indicated by the arrow shows whether the dynamic Young's modulus exhibits an increase or a decrease during the heating period.

It is apparent from Figure V.32 and Figure V.33 that the dynamic Young's modulus of both concrete and mortar test specimens always decreases during the heating period at a particular test temperature. The reduction in Young's modulus during the heating period is usually between 1 GPa and 2 GPa. This corresponds to a percentage reduction of between 3% and 6% for concrete test specimens and between 4% and 8% for mortar specimens. For test specimens which underwent drying at temperatures of either 70°C, 100°C, 150°C, 250°C or 400°C there is no apparent difference to the reductions in dynamic Young's modulus during the heating period. It appears, therefore, that at the various temperature levels the reductions in dynamic Young's modulus originate from the same cause. A possible explanation for the reductions in Young's modulus during the heating period is that microcracking of the test specimens occurred as a result of tensile stresses caused by either contraction of the cement paste relative to aggregate, or incompatible differential movement of the mix constituents during cooling. However, it should be remembered that for test specimens which underwent drying at either 70°C, 100°C, or 150°C, the compressive strength increases during the heating period. Thus the reduction in dynamic Young's modulus at these temperature levels could not have been caused by microcracking.

At a test temperature of 250°C the compressive strength of test specimens does not increase during the heating period, and at 400°C the compressive strength decreases during the heating period. It is possible, therefore, that the reductions in dynamic Young's modulus at these temperature levels is partly caused by microcracking.

The above conclusion, viz. that the reduction in dynamic Young's modulus during the heating period for test specimens which underwent drying at temperatures up to 150°C is not caused by the same effect as the reduction in dynamic Young's modulus for specimens which underwent drying at either 250°C or 400°C, is further substantiated by the data plotted in Figure V.34 and Figure V.35. In Figure V.34 the mean coded values of dynamic Young's modulus * for test specimens made from the concrete mixes are plotted against the percentage water loss of test specimens *. Figure V.35 illustrates the data for test specimens made from the mortar mixes.

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* This data is given in APPENDIX V.1.

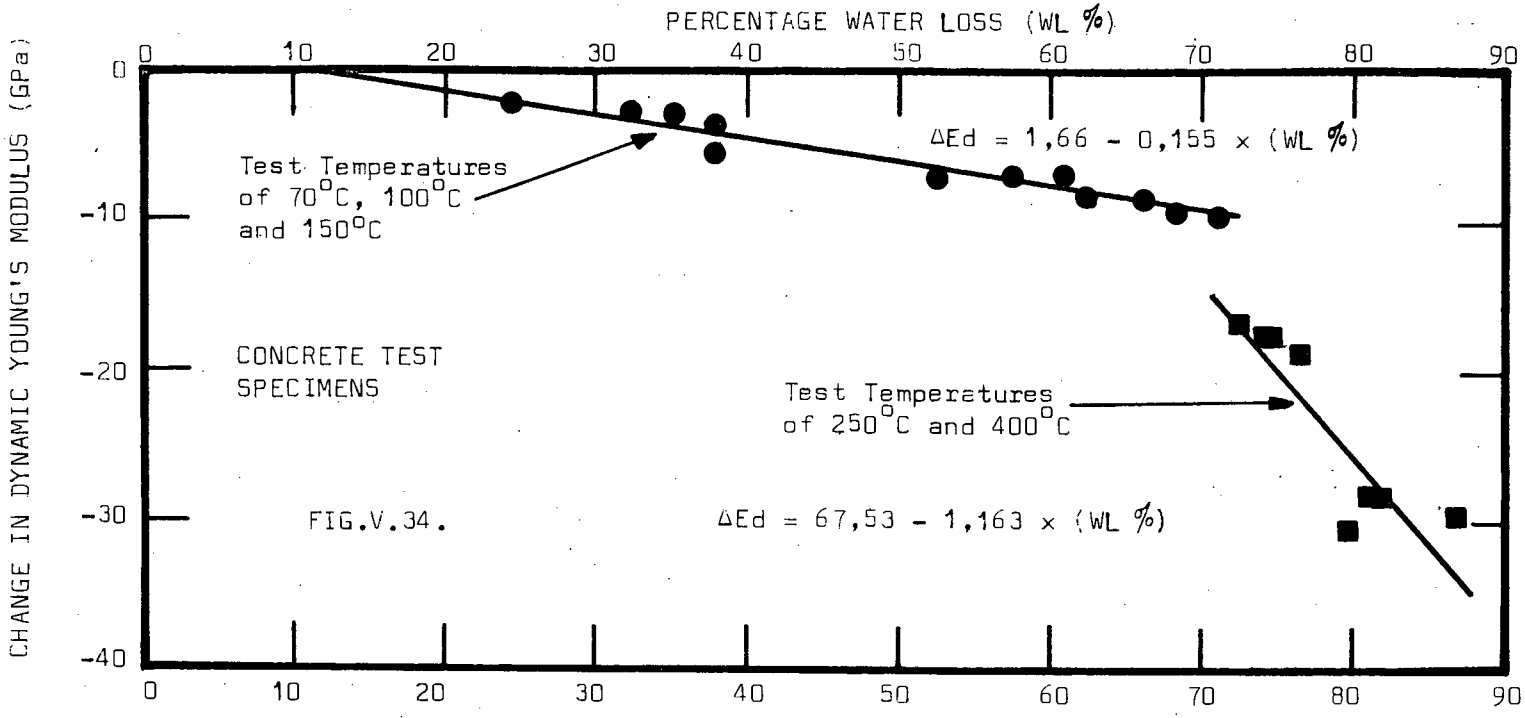

FIG.V.34.

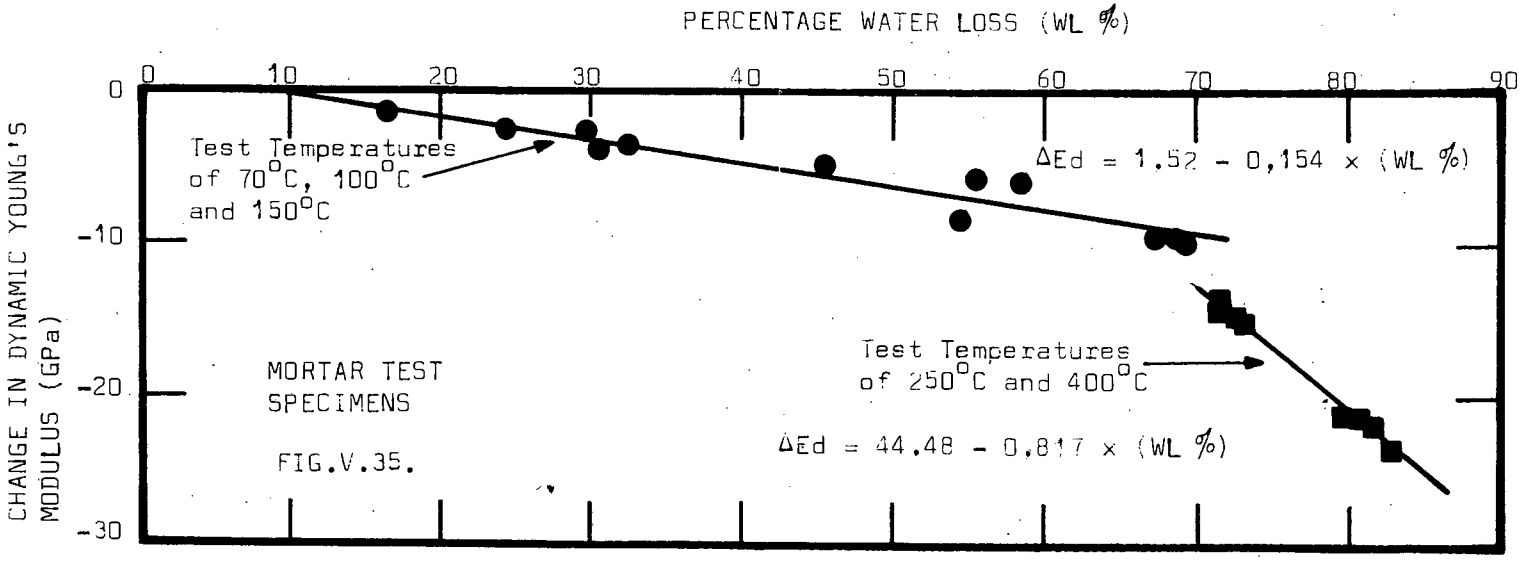

FIG.V.35.

FIG.V.34. and FIG.V.35: The change in dynamic Young's modulus (after cooling) plotted against the percentage Water Loss for Concrete and Mortar Specimens respectively.

It is immediately apparent for both concrete and mortar test specimens that the data fall into two categories:

(i) Test specimens which underwent drying at test temperatures of either 70°C, 100°C or 150°C, and

(ii) Test specimens which underwent drying at test temperatures of either 250°C or 400°C.

For each of the above categories a linear regression analysis was performed using the coded value of dynamic Young's modulus as the dependent variable and percentage water loss as the independent variable. At test temperatures of 70°C, 100°C and 150°C the regression equation is;

$\Delta Ed = 1,66 - 0,155\ (WL\%)$ for concrete test specimens, and
$\Delta Ed = 1,52 - 0,154\ (WL\%)$ for mortar test specimens.

where ΔEd = the change in dynamic Young's modulus (GPa)
$WL\%$ = the percentage water loss.

The above equations suggest that for test specimens which underwent drying at either 70°C, 100°C or 150°C, the initial reduction in dynamic Young's modulus at these temperatures, as well as the reduction in dynamic Young's modulus during the heating period, is primarily caused by the loss of evaporable water from the capillary pores and gel pores of the cement paste. The removal of evaporable water constitutes the removal of an incompressible phase from within the paste and consequently Young's modulus is reduced. The fact that the respective constants and regression coefficients in the above two equations are in such good agreement, is thought to indicate that the coarse aggregate did not affect the reductions in dynamic Young's modulus of specimens heated to these temperature levels.

At temperature levels of 70°C, 100°C and 150°C a further two effects may also have contributed to the reduction in dynamic Young's modulus of test specimens. The first of these is the dissolution of crystals of $Ca(OH)_2$ as a result of the hydrostatic compressive stress imposed by drying shrinkage and causing precipitation of either $CaCO_3$ or $Ca(OH)_2$ in spaces free from stress *. The compressibility of the cement paste may thus be increased and be manifest as a reduction in dynamic Young's modulus. The second of these effects is the initiation of stable microcracks which may not necessarily be detrimental to the compressive strength. However, there is no evidence that these effects are significant.

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* This was discussed in CHAPTER 4.

For test temperatures of 250°C and 400°C the regression equation is;

$\Delta Ed = 67,53 - 1,163\ (WL\%)$ for concrete test specimens, and
$\Delta Ed = 44,48 - 0,817\ (WL\%)$ for mortar test specimens.

where ΔEd = change in dynamic Young's modulus (GPa)
$WL\%$ = percentage water loss.

It is thought that at test temperatures of 250°C and 400°C the initial reduction in dynamic Young's modulus is due to both the loss of evaporable water during the heating period and unstable microcracking within test specimens as a result of incompatible differential movement of the mix constituents. The additional reduction in dynamic Young's modulus during the heating period is probably only associated with the second of the above effects, viz. microcracking due to cement paste contraction relative to aggregate particles during the loss of non-evaporable water. It is interesting to note from the equations for test specimens cooled from 250°C and 400°C that the reduction in dynamic Young's modulus is greater for concrete test specimens than for mortar test specimens. Consider a percentage water loss of 80% . Substituting in the above equations, the change in dynamic Young's modulus is approximately 17 GPa for mortar test specimens and 20 GPa for concrete test specimens. It appears, therefore, that the coarse aggregate had an effect on the reduction in dynamic Young's modulus of concrete specimens heated to either 250°C or 400°C. This is in accordance with the results of the statistical analysis.

It is thought that the above results indicate again that for test specimens which underwent drying at temperatures of either 70°C, 100°C or 150°C the stresses which occur as a result of incompatible differential movement between the mix constituents, are relieved by creep. At test temperatures of 250°C and 400°C the absence of intercrystalline water curtails the mobility of the paste, i.e. bonding between the gel crystallites is predominantly solid-solid bonding. Consequently, the stresses which arise from either;

(i) contraction of the paste relative to aggregate (as a result of the loss of non-evaporable water), or

(ii) the difference between the coefficient of thermal expansion of cement paste and aggregate (during cooling of specimens),

are not relieved by creep but by microcracking.

Figure V.32 and Figure V.33 show that the dynamic Young's modulus of both concrete and mortar test specimens which remained fully saturated at test temperatures of either 70°C or 100°C, decreases with time during the heating period at these temperatures. The reductions in dynamic Young's modulus during the heating period are between 1 GPa and 2 GPa. These reductions are approximately of the same magnitude as those which occurred for test specimens which underwent drying during heating. The above reductions in dynamic Young's modulus cannot be associated with water loss, since these test specimens remained fully saturated during heating. Also, the reductions cannot be the result of microcracking, since it was found that the compressive strength of specimens which remained fully saturated at either 70°C or 100°C did not decrease during the heating period; at 100°C the compressive strength of both mortar and concrete specimens exhibited an increase during the heating period. It should be noted, however, that microcracking of test specimens may have been a significant factor in causing part of the initial reduction in dynamic Young's modulus since this is accompanied by a reduction in the compressive strength.

It is thought that the decrease in the dynamic Young's modulus of saturated test specimens during the heating period is related to the chemical reactions which were discussed in CHAPTER 4. It is possible, too, that these chemical reactions are largely responsible for the initial reductions in dynamic Young's modulus. However, no reason can be suggested for the fact that the dynamic Young's modulus decreases during the heating period whereas the compressive strength increases during the heating period as a result of the chemical reaction(s).

5.2.2 Specimens tested after cooling and re-immersion in water

The effect of heating time on the dynamic Young's modulus of specimens tested after cooling and 7 days re-immersion in water is illustrated in Figure V.36 and Figure V.37. In Figure V.36 the mean coded values of dynamic Young's modulus are illustrated for test specimens made from the concrete mixes. Figure V.37 illustrates the data for test specimens made from the mortar mixes.

It is apparent from Figure V.36 and Figure V.37 that for test specimens which underwent drying at temperatures of either 70°C, 100°C or 150°C, the dynamic Young's modulus decreases during the heating period. Furthermore, comparing Figure V.36 and Figure V.37 to Figure V.32 and Figure V.33 respectively, it is apparent that the dynamic Young's modulus of both concrete and mortar specimens which were re-immersed in water after cooling from these temperatures is only between 1 GPa and 3 GPa greater than

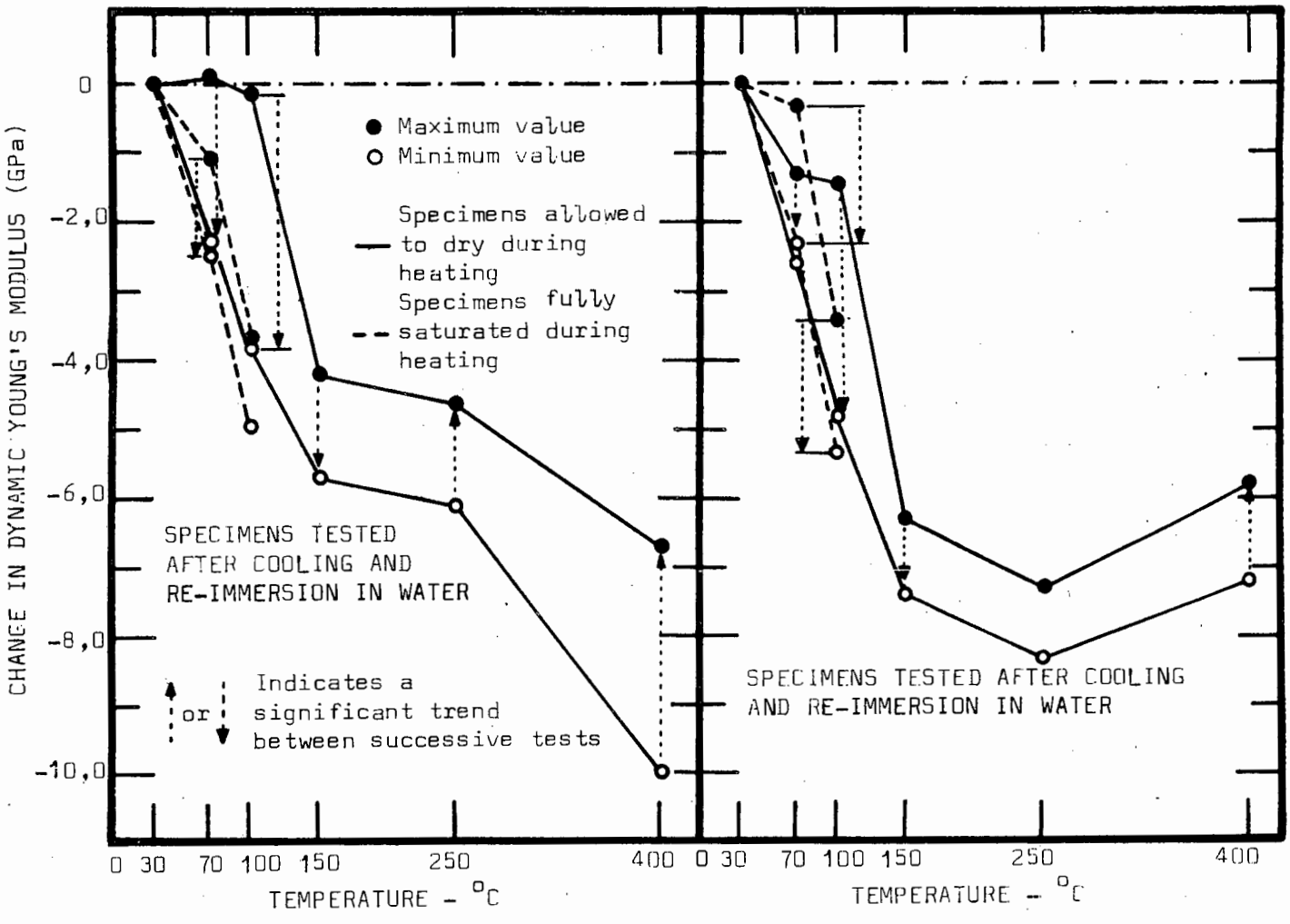

FIG.V.36: The mean change in dynamic Young's modulus for test specimens made from the concrete mixes.

FIG.V.37: The mean change in dynamic Young's modulus for test specimens made from the mortar mixes.

the dynamic Young's modulus of specimens tested immediately after cooling. In the previous section it was suggested that the reduction in dynamic Young's modulus of test specimens which underwent drying at either 70°C, 100°C or 150°C is primarily due to the loss of evaporable water. Consequently, upon re-immersion of these test specimens, it would be expected that the replacement of the evaporable water would eliminate the reductions in dynamic Young's modulus, i.e. the values of dynamic Young's modulus after re-immersion should be approximately the same as the mean control value of dynamic Young's modulus for unheated test specimens. The abovementioned results indicate no such trend.

It is thought that the reduction in dynamic Young's modulus of test specimens which were re-immersed in water after cooling from temperatures of either 70°C, 100°C or 150°C indicates that microcracking occurred within these test specimens as a result of the replacement of evaporable water. In PART I : CHAPTER 4 it was shown that the tensile stresses which result from a contraction of cement paste relative to aggregate are higher than the tensile stresses which cement paste, or mortar, can withstand. It was also shown that the tensile stresses caused by an expansion of paste relative to aggregate are many times higher than the tensile stresses caused by paste contractions relative to aggregate[46]. During the heating period, the paste contracts relative to aggregate particles. The loss of pore water, intercrystalline water and intracrystalline water (due either to temperature level or hydrostatic creep) results in the formation of new physical or chemical bonds within the paste. Also the paste creeps in order to relieve stressed caused by contraction of the paste relative to aggregate. Upon re-immersion of test specimens the cement paste swells. It is likely that the swelling of the paste relative to aggregate particles causes large tensile stresses either within the paste or at the paste aggregate interface. These stresses will be relieved by creep. However, it must be remembered that both creep, and creep rate, are lower at room temperature than at the temperature at which the contraction of paste relative to aggregate originally occurred. It is possible, therefore, that the tensile stresses are of sufficiently great magnitude to result in sub-critical microcracking within test specimens. This would explain the reduction in compressive strength as well as the reduction in dynamic Young's modulus of test specimens which underwent drying at either 70°C, 100°C or 150°C and were re-immersed in water for 7 days before testing.

From Figure V.36 and Figure V.37 it is apparent that the dynamic Young's modulus of test specimens cooled from either 250°C or 400°C and immersed in water usually increases during the heating period. This trend is

opposite to that exhibited by the dynamic Young's modulus of test specimens which were tested immediately after cooling from either 250°C or 400°C. Furthermore, these values of dynamic Young's modulus for both concrete and mortar specimens are significantly higher than the values obtained from test specimens which were tested immediately after cooling from either 250°C or 400°C. The difference between dynamic Young's modulus for the two test cases ranges from 6 GPa to 15 GPA for cooling from 250°C and 14 GPa to 26 GPa for specimens cooled from 400°C. It is felt that these results substantiate the conclusions that:

(i) The removal/replacement of evaporable water has a large influence on the dynamic Young's modulus. This is because the evaporable water constitutes an incompressible phase within the cement paste.

(ii) Microcracking occurred within test specimens which were cooled from either 250°C or 400°C. The extent of the microcracking increases as the heating time at these test temperatures increases. Consequently, test specimens which were subjected to these temperatures for the longest time period can imbibe more water during re-immersion. Hence the dynamic Young's modulus appears to increase during the heating period for specimens which were cooled and re-immersed in water at the successive test times during the heating period.

It should be noted, however, that the increase in dynamic Young's modulus of these test specimens may be partly due to hydration of dehydrated products. At test temperatures of 250°C and 400°C the tobermorite gel ($C_{1,62}\ S\ H_{1,5}$) exhibits a loss of non-evaporable water; the dehydration residue is β - C S. It is possible, therefore, that hydration occurs when test specimens are re-immersed in water.

Figure V.36 and Figure V.37 also indicate that the coded values of dynamic Young's modulus for test specimens which remained fully saturated at either 70°C or 100°C and were re-immersed in water for 7 days, usually decreases for tests performed at the successive times during the heating period. This is similar to the trend exhibited by the dynamic Young's modulus of test specimens which remained fully saturated and were tested immediately after cooling. However, the former values of dynamic Young's modulus are between 1 GPa and 2 GPa greater than the latter values. It is likely that the difference in these values of dynamic Young's modulus is due to additional hydration of test specimens during the 7 day re-immersion period.

CHAPTER 6 : ULTRASONIC PULSE VELOCITY

6.1 Summary of Results

6.1.1 Specimens tested after cooling

The ultrasonic pulse velocity of both concrete and mortar test specimens is always adversely affected by heating. In general, the higher the temperature level, the greater the reduction in ultrasonic pulse velocity. This is in agreement with the results of Zoldners[2].

The maximum percentage reductions in pulse velocity of test specimens which underwent drying during heating were approximately:

8% for concrete test specimens and 10% for mortar test specimens at 70°C;
10% " " " " " 15% " " " " " 100°C;
14% " " " " " 23% " " " " " 150°C;
23% " " " " " 35% " " " " " 250°C;
45% " " " " " 50% " " " " " 400°C.

The pulse velocity of mortar test specimens which underwent drying during heating is always more reduced than the pulse velocity of the corresponding concrete test specimens. However, it must be remembered that mortar test specimens have a greater total water loss than concrete test specimens *. Since the ultrasonic pulse velocity is influenced by water loss[19] the greater reduction of pulse velocity for mortar specimens is not unexpected.

Test specimens which remained fully saturated at test temperatures of either 70°C or 100°C always exhibit a reduction in ultrasonic pulse velocity. This reduction in pulse velocity occurs despite the fact that no water loss occurred during heating. The maximum percentage reductions in pulse velocity were approximately 5% for both concrete and mortar specimens at 70°C. At 100°C the maximum percentage reduction was approximately 5% for concrete test specimens and 10% for mortar specimens.

6.1.2 Specimens tested after cooling and re-immersion in water

The reduction in pulse velocity for test specimens which underwent drying at either 70°C, 100°C, 150°C, 250°C or 400°C and were cooled and re-immersed in water for 7 days before testing, is always smaller than the reduction in pulse velocity of specimens which were tested immediately after cooling from these temperature levels. The percentage difference between the respective

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* The percentage water loss, as a percentage of the amount of water in specimens prior to heating, is the same for concrete and mortar test specimens.

reductions ranges between 5% for specimens cooled from 70°C to 40% for test specimens cooled from 400°C. Test specimens which remained fully saturated at either 70°C or 100°C exhibit reductions in pulse velocity which do not differ appreciably for the abovementioned two test cases.

For test specimens which underwent drying the maximum percentage reductions in pulse velocity were approximately:

5% for both concrete and mortar test specimens at 70°C;
7% " concrete test specimens and 13% for mortar test specimens at 100°C;
10% " " " " " 19% " " " " " 150°C;
7% " " " " " 15% " " " " " 250°C;
8% " " " " " 13% " " " " " 400°C.

It is apparent from the results that the reduction in pulse velocity for mortar test specimens which underwent drying at either 100°C, 150°C, 250°C or 400°C and were immersed in water for 7 days is always greater than the reduction for the corresponding concrete test specimens. Since these pulse velocity results apply to specimens which were re-saturated and, therefore, are not affected by the difference in total water loss between concrete and mortar specimens, this appears to substantiate the conclusion that the physical properties of the concrete test specimens were primarily affected by changes which occurred in the mortar phase.

6.2 The Effect of Heating Time

6.2.1 Specimens tested after cooling

The effect of heating time on the ultrasonic pulse velocity is illustrated in Figure V.38 and Figure V.39 for concrete and mortar test specimens respectively. Each of Figure V.38 and Figure V.39 show the maximum and minimum mean coded values of ultrasonic pulse velocity at the various temperature levels. At certain of the test temperatures an arrow is drawn from the minimum value to the maximum value, or vice versa: this shows that the statistical analysis indicates a significant trend between the successive tests performed during the heating period at a particular temperature.

It is apparent from Figure V.38 and Figure V.39 that the pulse velocity of both concrete and mortar test specimens which remained fully saturated at either 70°C or 100°C, always decreases during the heating period. Figure V.38 and Figure V.39 also show that the pulse velocity of test specimens which underwent drying at temperatures of either 70°C, 100°C, 150°C, 250°C or 400°C usually decreases during the heating period. The exception to this is the

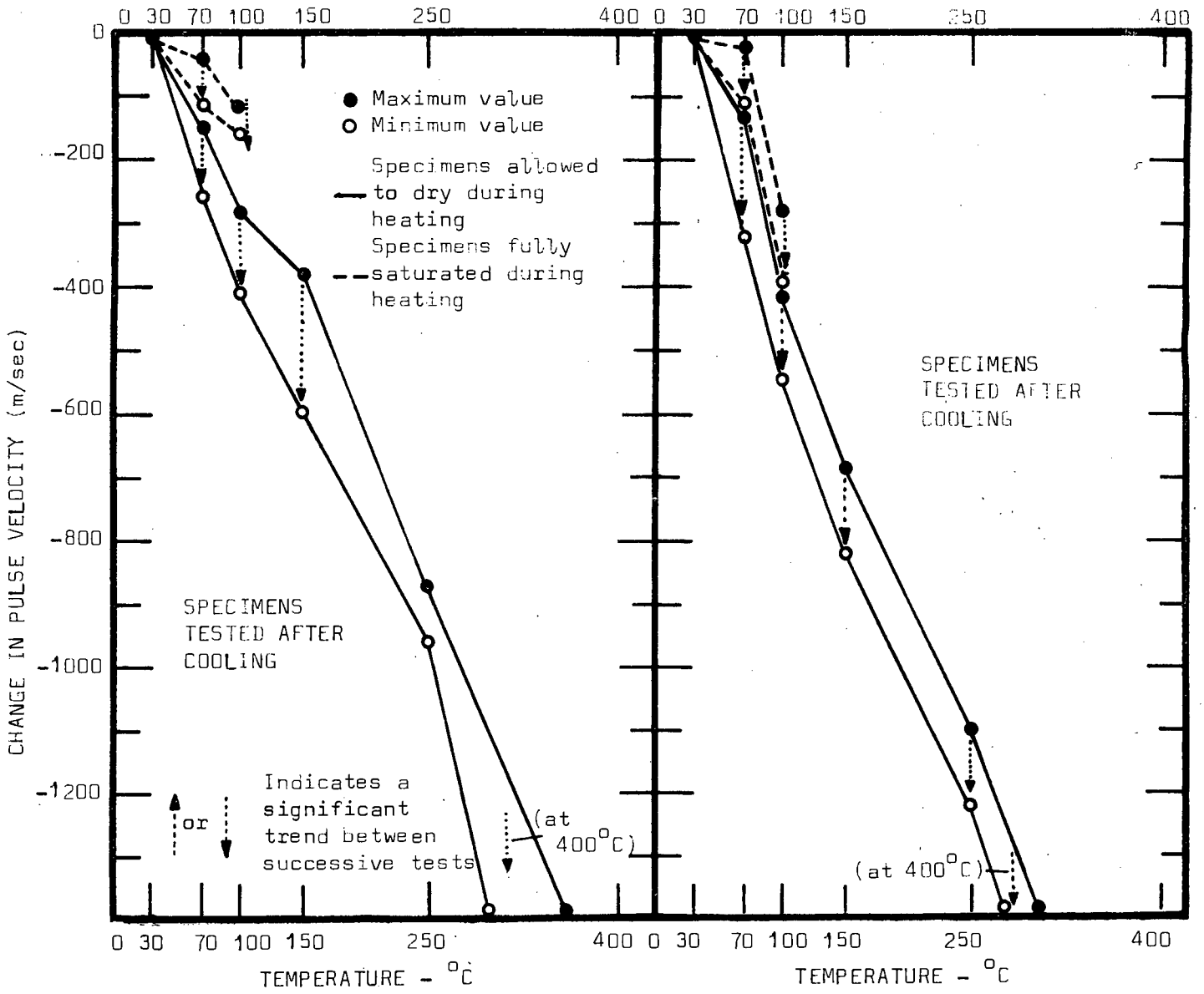

FIG.V.38: The mean change in ultrasonic pulse velocity for test specimens made from the concrete mixes.

FIG.V.39: The mean change in ultrasonic pulse velocity for test specimens made from the mortar mixes.

pulse velocity of concrete specimens which were heated to a test temperature of 250°C. This data exhibits no significant trend between the tests performed at the successive test times.

The abovementioned behavioural patterns are almost exactly similar to the behavioural patterns exhibited by the results of dynamic Young's modulus of concrete and mortar test specimens (illustrated in Figure V.32 and Figure V.33). It is thought that the factors which affect the ultrasonic pulse velocity specimens tested after cooling are exactly the same as those which affect dynamic Young's modulus. These factors were discussed in the previous Chapter, section 5.2.1.

The only difference between the factors which affect dynamic Young's modulus and pulse velocity respectively, is that the reduction in dynamic Young's modulus occurs by virtue of the removal of an incompressible phase, whereas the reduction in pulse velocity is caused by the slower transmission of ultrasonic waves across air-filled pores. However, both processes involve the loss of evaporable water and the pulse velocity data exhibits exactly the same trend as the dynamic Young's modulus if plotted against the percentage water loss. In Figure V.40 and Figure V.41 the coded values of ultrasonic pulse velocity are plotted against percentage water loss for concrete and mortar test specimens respectively. It is immediately apparent that these data fall into the same two categories as found previously for the dynamic Young's modulus data, viz:

(i) Test specimens which underwent drying at temperatures of either 70°C, 100°C or 150°C, and

(ii) Test specimens which underwent drying at temperatures of either 250°C or 400°C.

The regression equations obtained from the data corresponding to (i) above are

$$\Delta PV = 78{,}61 - 8{,}56\ (WL\%) \text{ for concrete test specimens}$$

$$\Delta PV = 23{,}85 - 11{,}49\ (WL\%) \text{ " mortar " "}$$

where ΔPV is the change in ultrasonic pulse velocity (m/sec).

$WL\%$ is the percentage water loss.

These equations indicate that the reduction in pulse velocity at a particular percentage water loss is always greater for mortar test specimens than for

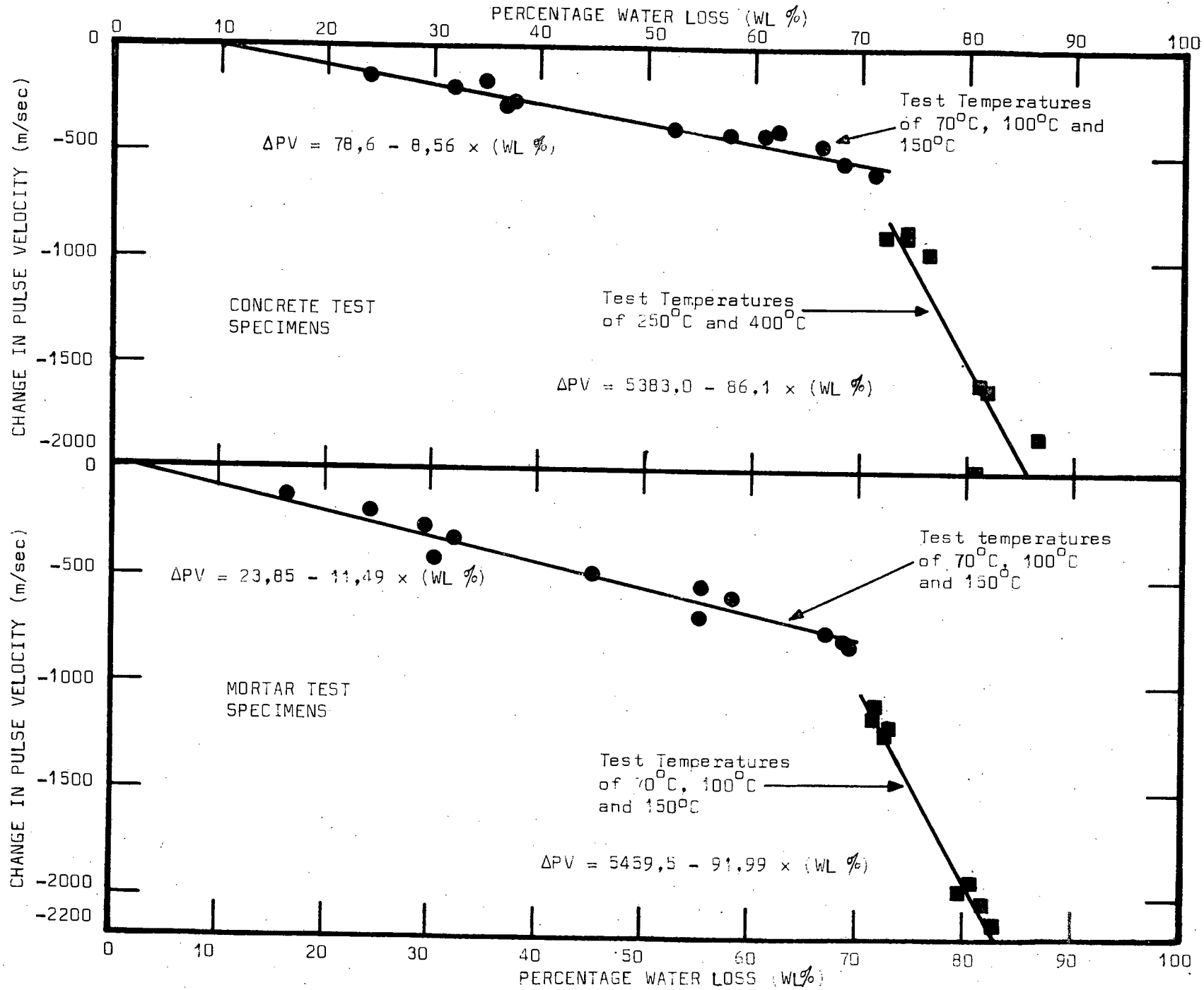

FIG.V.40 : and FIG.V.41 : The change in Pulse Velocity (after cooling) plotted against the percentage Water Loss for Concrete and Mortar Specimens respectively.

concrete test specimens.

The equations obtained from a linear regression analysis of the coded values of pulse velocity against percentage water loss for specimens cooled from either 250°C or 400°C are:

$$\Delta PV = 5383,0 - 86,10\ (WL\%) \text{ for concrete test specimens}$$

$$\Delta PV = 5459,5 - 91,99\ (WL\%) \text{ " mortar " "}$$

The respective constants and regression coefficients for these two equations are approximately the same, i.e. at a particular percentage water loss the reduction in pulse velocity of the concrete specimens is approximately the same as the reduction in pulse velocity for mortar specimens. This probably indicates that the microcracking effect is a highly significant factor in the reductions in pulse velocity at these temperatures. This was discussed previously in CHAPTER 5 : section 5.2.1.

6.2.2 Specimens tested after 7 days re-immersion in water

The effect of heating time on the pulse velocity of specimens which were tested after cooling and re-immersion is illustrated in Figure V.42 and Figure V.43. Figure V.42 illustrates the mean coded values of pulse velocity for the concrete test specimens and Figure V.43 the coded values for mortar specimens.

It is apparent from Figure V.42 and Figure V.43 that:

(i) The pulse velocity of test specimens which remained fully saturated at either 70°C or 100°C usually decreases during the heating period.

(ii) The pulse velocity of test specimens which underwent drying at either 70°C, 100°C or 150°C, usually decreases during the heating period.

(iii) The pulse velocity of test specimens which underwent drying at either 250°C or 400°C usually increases during the heating period.

For each of (i), (ii) and (iii) above there are instances in which the pulse velocity data do not exhibit these trends, i.e. at certain of the temperature levels the pulse velocity does not change significantly during

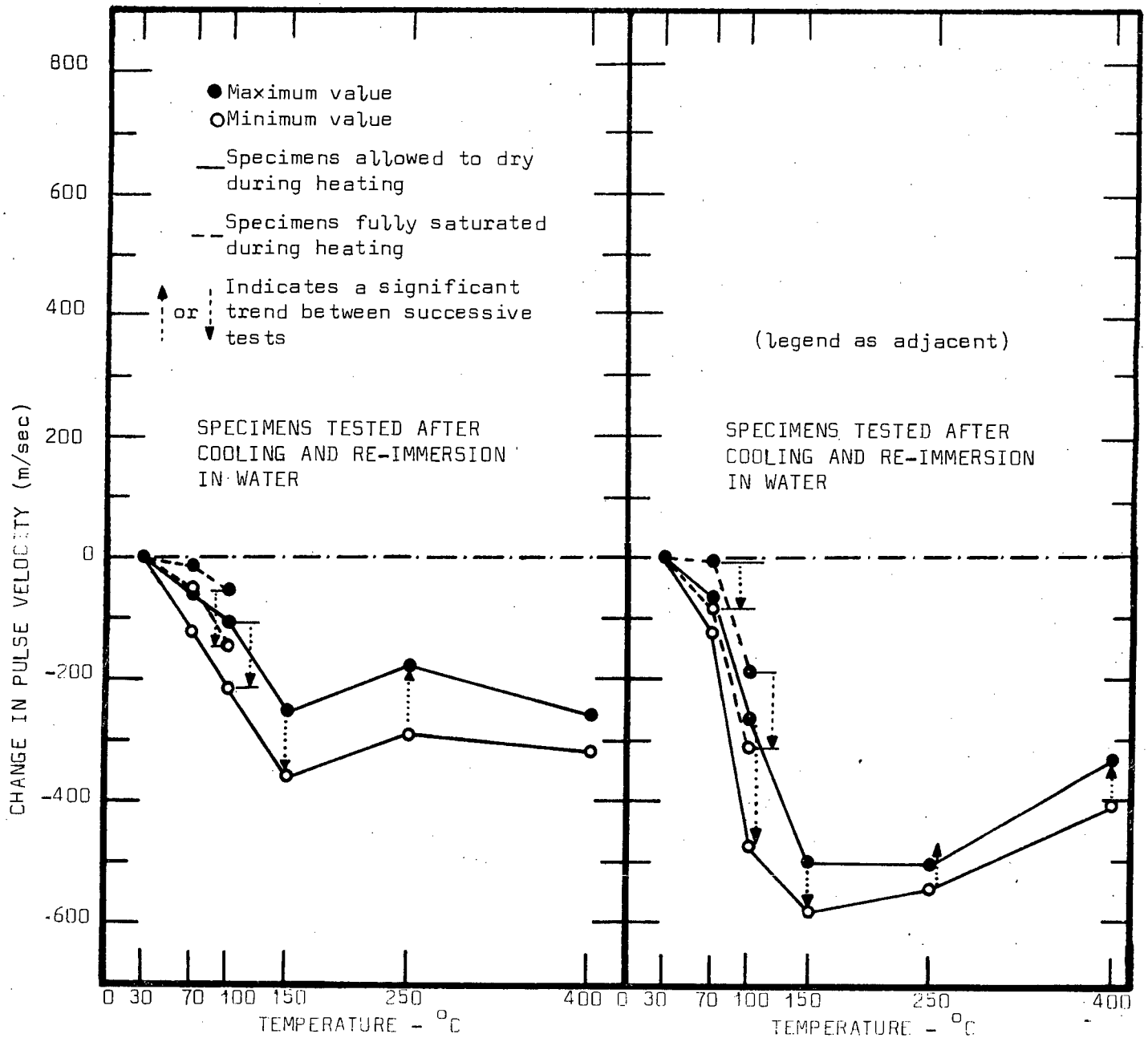

FIG.V.42: The mean change in pulse velocity for test specimens made from the three concrete mixes.

FIG.V.43: The mean change in pulse velocity for test specimens made from the three mortar mixes.

the heating period. However, the general trends exhibited by these data are the same as those found for the dynamic Young's modulus of test specimens which were re-immersed in water after cooling (illustrated in Figure V.37 and Figure V.38). It is thought, therefore, that the factors which caused the abovementioned trends to the pulse velocity data are exactly the same as those which affected the dynamic Young's modulus. These were discussed in CHAPTER 5 : section 5.2.2.

CHAPTER 7 : POISSON'S RATIO

7.1 Summary of Results

7.1.1 Specimens tested after cooling

Poisson's ratio was calculated from the measured values of ultrasonic pulse velocity, dynamic Young's modulus and water loss *.

At all temperature levels the percentage change in Poisson's ratio of mortar test specimens is different to the percentage change in Poisson's ratio of concrete test specimens. Furthermore, at certain temperature levels the value of Poisson's ratio for concrete test specimens is greater than the mean control values of Poisson's ratio whereas the value of Poisson's ratio for mortar test specimens is less than the mean control value.

The values of Poisson's ratio (expressed as a percentage of the mean control value of Poisson's ratio) for test specimens which underwent drying and were tested at the end of the heating period, are between;

64%	and	96%	for	concrete	test	specimens	at 70°C,
75%	"	86%	"	mortar	"	"	" "
89%	"	107%	"	concrete	"	"	" 100°C,
60%	"	80%	"	mortar	"	"	" "
90%	"	95%	"	concrete	"	"	" 150°C
57%	"	85%	"	mortar	"	"	" "
105%	"	123%	"	concrete	"	"	" 250°C
81%	"	98%	"	mortar	"	"	" "
128%	"	142%	"	concrete	"	"	" 400°C
105%	"	125%	"	mortar	"	"	" "

It appears that, in general, the values of Poisson's ratio for concrete test specimens decrease at temperature levels of either 70°C, 100°C or 150°C and the values increase at temperature levels of either 250°C or 400°C. The values of Poisson's ratio for mortar test specimens exhibit almost exactly the same trend. However, at a test temperature of 250°C the values of Poisson's ratio, although greater than the values of Poisson's ratio at 150°C, are not greater than the mean control values of Poisson's ratio.

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* The method of calculating Poisson's ratio is given in APPENDIX 1.2.

Results which conform to the abovementioned trend are reported by Crispino[8] for both a limestone aggregate concrete and barite aggregate concrete. Poisson's ratio was not determined dynamically but from strain measurements on unsealed concrete specimens after they had cooled to room temperature. It was found that at 110°C both concretes exhibited values of Poisson's ratio which were lower than the Poisson's ratio values measured at room temperature. At temperatures of 300°C to 500°C, Poisson's ratio increased with respect to the value of Poisson's ratio of an unheated specimen. In general, the higher the temperature the greater the increase in Poisson's ratio. Crispino[8] attributes the increase in Poisson's ratio to microcracking of the concrete. However, Phillеo[29] and Marechal[13] report data which indicate that Poisson's ratio decreases progressively as the test temperature increases, i.e. these authors [13; 29] do not report a subsequent increase in Poisson's ratio at higher temperature levels. These conflicting results may have been partly due to the effect of heating time. This is discussed in the following section.

It is interesting that Phillеo[29] indicates that Poisson's ratio determinations by the dynamic method are erratic and that test results exhibit wide variations. This was found in the present investigation. The reason for the large variation in the values of Poisson's ratio is that this parameter is sensitive to errors in determining the resonant frequencies *; a 1% error in resonant frequency may result in a 20% error in the calculated value of Poisson's ratio.

Test specimens which remained fully saturated at temperatures of either 70°C or 100°C usually exhibit values of Poisson's ratio which are larger than the values for unheated test specimens. At 70°C the values of Poisson's ratio range between 101% and 113%, and at 100°C the value range between 96% and 111%. These results do not agree with the data of Nishizawa and Okamura[12]; these investigators found that Poisson's ratio of sealed concrete test specimens heated to 90°C does not differ from the value of Poisson's ratio at room temperature.

7.1.2 Specimens tested after cooling and 7 days re-immersion in water

The values of Poisson's ratio for test specimens which underwent drying and were re-immersed after cooling, range between:

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* In the dynamic Young's modulus determination.

84%	and	104%	for	concrete	test specimens	at 70°C
88%	"	112%	"	mortar	"	" " "
88%	"	113%	"	concrete	"	" " 100°C
75%	"	100%	"	mortar	"	" " "
90%	"	105%	"	concrete	"	" " 150°C
93%	"	110%	"	mortar	"	" " "
98%	"	111%	"	concrete	"	" " 250°C
98%	"	110%	"	mortar	"	" " "
89%	"	123%	"	concrete	"	" " 400°C
88%	"	126%	"	mortar	"	" " "

These data do not exhibit the same trend as the values of Poisson's ratio determined on test specimens immediately after cooling. However, it does appear that for test specimens which were cooled from either 250°C or 400°C and immersed in water, the values of Poisson's ratio are generally greater than the values for test specimens which were cooled from temperature levels of either 70°C, 100°C or 150°C.

The values of Poisson's ratio for test specimens which remained fully saturated at either 70°C or 100°C range between 100% and 114% for both concrete and mortar specimens. These values are approximately the same as the values of Poisson's ratio determined on test specimens which were tested immediately after cooling.

7.2 The Effect of Heating Time

7.2.1 Specimens tested after cooling

The effect of heating time on Poisson's ratio of specimens which were tested after cooling is illustrated in Figure V.44 and Figure V.45. Figure V.44 shows the mean coded values of Poisson's ratio for test specimens made from the concrete mixes and Figure V.45 the mean coded values for test specimens made from the mortar mixes. The arrows drawn in Figure V.44 and Figure V.45 show that the statistical analysis indicates a statistically significant trend between the tests performed at the successive times during the heating period. The direction indicated by the arrow in these diagrams shows whether the values of Poisson's ratio increase of decrease during the heating period.

It is apparent from Figure V.44 and Figure V.45 that the behaviour of Poisson's ratio of test specimens which underwent drying during heating,

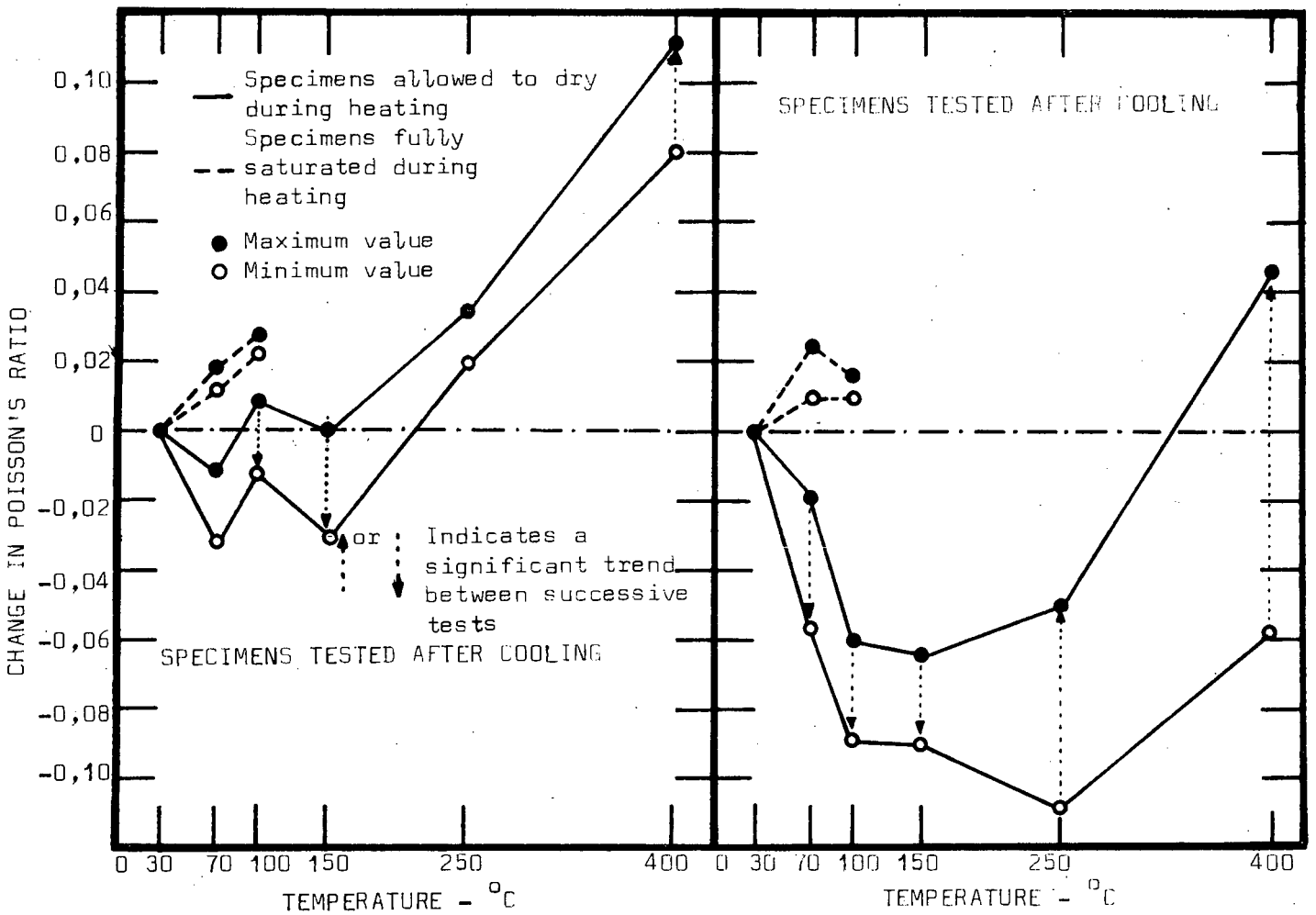


FIG.V.44: The mean change in Poisson's ratio for test specimens made from the concrete mixes.

FIG.V.45: The mean change in Poisson's ratio for test specimens made from the mortar mixes.

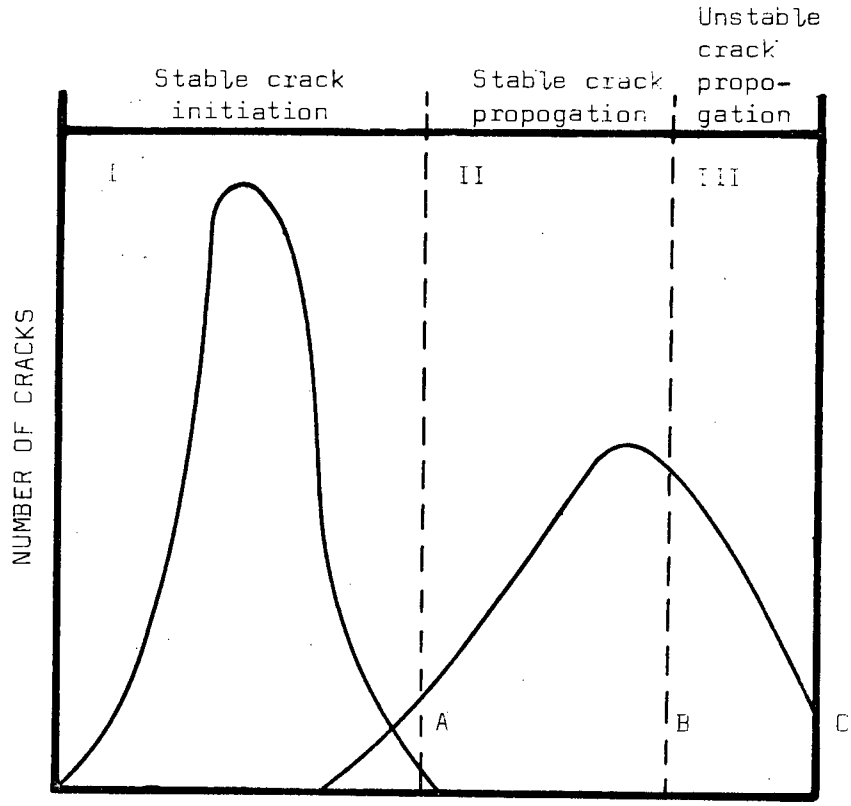
fall into two categories, viz:

(i) Test specimens which underwent drying at either 70°C, 100°C or 150°C. Poisson's ratio of these test specimens is usually reduced. In general, the higher the temperature the greater the reduction in Poisson's ratio. Furthermore, the values of Poisson's ratio usually decrease during the heating period.

(ii) Test specimens which underwent drying at either 250°C or 400°C. These values of Poisson's ratio usually increase during the heating period. Furthermore, the values of Poisson's ratio are usually greater than the values of Poisson's ratio at 150°C, and in many instances greater than the values of Poisson's ratio for unheated control specimens.

It is thought that the above test results are conclusive evidence that unstable microcracking occurred within test specimens heated to temperatures above 250°C, and furthermore, that the microcracking increased progressively during the heating period. With regard to the behaviour of Poisson's ratio it is worth noting some general comments by Neville[30]. If concrete is subjected to an increasing compressive load "the volumetric strain first decreases, i.e. the effect of a monotonically increasing compressive stress is a densification of the concrete. However, at some point the rate of change of volume becomes zero and hereafter an increase in volumetric strain takes place". The point of change heralds the development of cracking to such an extent that the concrete is strictly speaking no longer a continuous body, and Poisson's ratio increases rapidly. However, it should be noted that the value of Poisson's ratio at this stage is only an apparent value since the concrete test specimen is no longer a continuous body.

In this regard it is interesting to compare the Poisson's ratio data in Figure V.46 to the results of residual linear deformation shown in Figure V.10 and Figure V.11 in CHAPTER 3. The trends exhibited by the two sets of data are almost exactly similar. Furthermore, the general pattern to these graphs is in good agreement with the stress/volumetric strain relation of concrete[91] illustrated in Figure V.46. It appears that the effect of an increase in the test temperature is analogous to an increase in the compressive stress to which test specimens are subjected. At a value of compressive stress corresponding to approximately 80% of the short-term uni-axial strength, the limiting value of tensile strain within test specimens (in the lateral direction) is exceeded and this stage heralds the initiation of unstable crack



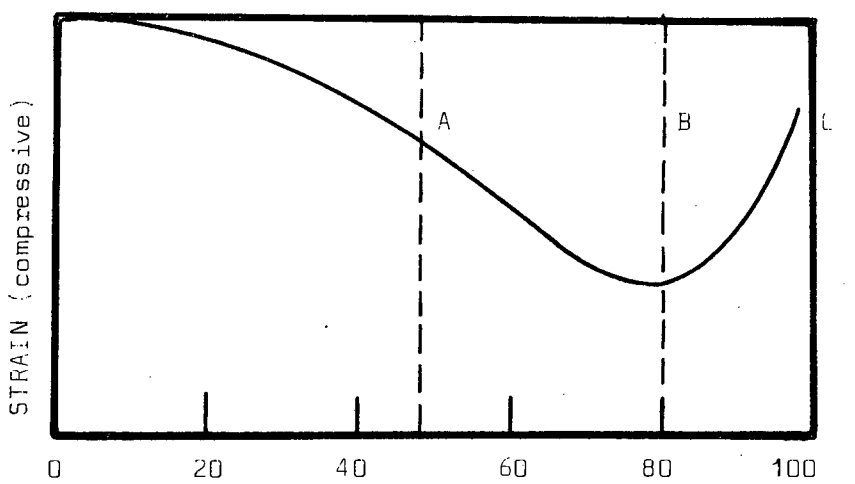


FIG.V.46: The stages in cracking in concrete in terms of the stress - volumetric strain relation (91).

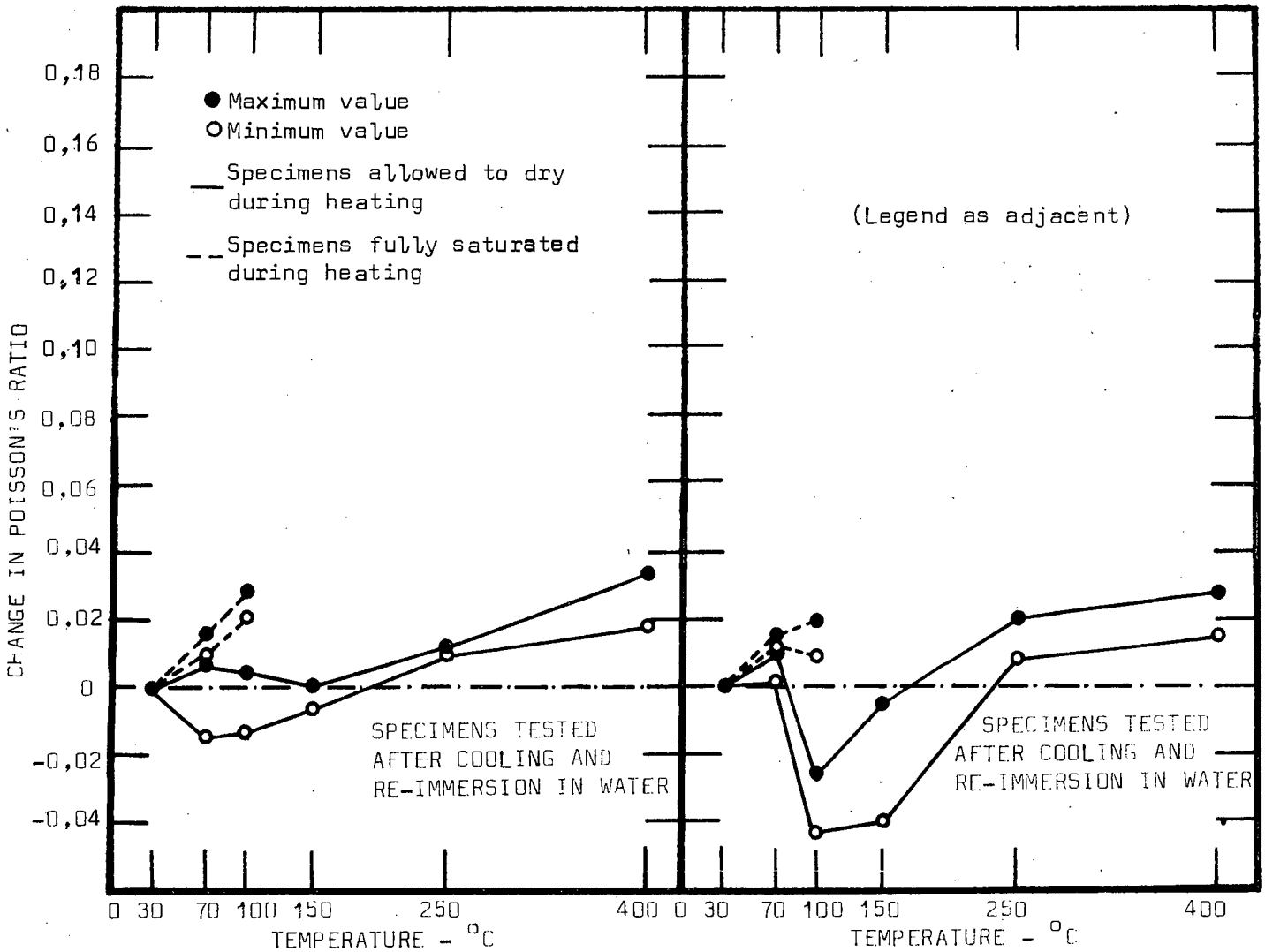


FIG.V.47: The mean change in Poisson's ratio for test specimens made from the concrete mixes.

FIG.V.48: The mean change in Poisson's ratio for test specimens made from the mortar mixes.

propagation. Consequently, the volumetric strain and Poisson's ratio of test specimens increases. This stage appears to correspond to a temperature level somewhere between 150°C and 250°C. The reasons for microcracking at these temperature levels have been previously discussed. The decrease in Poisson's ratio of test specimens which underwent drying at temperatures of either 70°C, 100°C or 150°C is probably due to densification of the cement paste under the action of the multiaxial hydrostatic compressive stress imposed by drying shrinkage.

Assuming that the above analogy is true, it is interesting to note that at temperature levels below 150°C a certain degree of stable crack initiation and stable crack propagation (sub-critical cracking) did occur within test specimens. However, it appears from the foregoing experimental results that this did not have a significant influence on the physical properties of test specimens which were tested immediately after cooling.

Poisson's ratio of test specimens which remained fully saturated during heating at either 70°C or 100°C and were tested immediately after cooling, is greater than the values of Poisson's ratio for unheated control specimens. The values of Poisson's ratio for these test specimens do not increase during the heating period. This may indicate that a certain degree of microcracking occurred within saturated test specimens during the time period when specimens were heated to the desired temperature levels. However, it is more probable that the increase in Poisson's ratio is associated with the formation of new hydration products as a result of the chemical reactions which occur when saturated test specimens are heated. These chemical reactions were discussed in CHAPTER 2 and CHAPTER 4.

7.2.2 Specimens tested after re-immersion in water

The coded values of Poisson's ratio for test specimens which were re-immersed in water after cooling are illustrated in Figure V.47 and Figure V.48 for concrete and mortar test specimens respectively. These data indicate no trends as regards the affect of heating time on the values of Poisson's ratio.

CHAPTER 8 : SUMMARY OF CONCLUSIONS

Based on the experimental results, the statistical analyses and the preceeding discussion, the following conclusions are believed warranted:

(i) The structural properties of concrete and mortar test specimens may change signficantly during the heating period at a particular temperature. The changes which occurred for test specimens which remained fully saturated during heating are not the same as the changes which occurred for test specimens which underwent drying during heating:-

For concrete and mortar test specimens which remained fully saturated at either 70°C or 100°C during heating, the property changes during the heating period are associated primarily with two chemical reactions: the first of these reactions occurs within the cement paste only, and the second reaction occurs between the cement paste and the siliceous aggregate used in this investigation. For test specimens which remained fully saturated during heating there is no conclusive evidence of microcracking in either concrete or mortar specimens.

For concrete and mortar specimens which underwent drying at test temperatures of either 70°C, 100°C or 150°C the changes in the measured properties are thought to be related mainly to the loss of water from the gel pores and capillary pores of the cement paste. At these temperature levels the presence of intercrystalline water (between adajacent gel crystals) is thought to facilitate creep of the cement paste in order to relieve stresses which occur as a result of incompatible differential movement between the mix constituents. It is thought that a certain degree of stable crack initiation and stable crack propagation may have occurred within test specimens at these temperature levels. This cracking did not have a significant influence on the physical properties of test specimens which were tested immediately after cooling. However, the experimental results indicate that the influence of microcracking is highly significant if these test specimens are re-saturated with water.

At test temperatures of either 250°C or 400°C the effect of unstable crack propagation, both during the heating period and during cooling

is thought to be a significant factor influencing the structural behaviour of both concrete and mortar test specimens. The microcracking of test specimens becomes apparent as a progressive decrease in compressive strength during the heating period, accompanied by an increase in Poisson's ratio of test specimens during the heating period. The microcracking during the heating period is associated with the loss of non-evaporable water; this causes an incompatible contraction of the cement paste to aggregate particles, and results in high tensile stresses within the paste. It appears that creep of the cement paste cannot relieve the stresses thus caused, and consequently cracking occurs. The inability of the cement paste to relieve these stresses by creep is thought to be associated with the fact that at these temperature levels the bonding within the paste is predominantly solid-solid bonding. At temperature levels of both 250°C and 400°C further microcracking occurs during the cooling of concrete and mortar test specimens. This is caused by the difference between the thermal expansion coefficients of the constituents.

(ii) At all the test temperatures the property changes which occurred for test specimens made from the various mortar mixes are usually either greater than, or equal to, the property change which occurred for test specimens made from the various concrete mixes. This substantiates the hypothesis that the presence of coarse aggregate is not necessarily detrimental to the structural behaviour of concrete at elevated temperature. The exception to this occurred for the dynamic Young's modulus of specimens tested after cooling from temperatures of either 250°C or 400°C; at these temperatures the dynamic Young's modulus of concrete test specimens is more reduced than the dynamic Young's modulus of mortar test specimens.

(iii) Temperature cycling had no additional effect on the reductions in the physical properties of either concrete or mortar test specimens at a particular temperature level. However, it is likely that this would not have been the case if test specimens had been subjected to a greater number of temperature cycles.

(iv) At a particular temperature level the property changes exhibited by test specimens are in many instances significantly different for the various concrete or the various mortar mixes. By comparing the property changes which occurred for test specimens made from :

(a) the two concrete (or mortar) mixes which differed only in water content;

(b) the two concrete (or mortar) mixes which differed only in volumetric concentration of aggregate.

it was found that there was no particular trend to the property changes which occurred, i.e. test specimens made from a particular mix (as in either (a) or (b) above) did not exhibit consistently better property behaviour at the various test temperatures than test specimens made from the other mix. In the absence of any conclusive trends as regards the influence of either the aggregate content or the water content on the behaviour of concrete at elevated temperature, it is concluded that this part of the investigation was unsuccessful.

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APPENDIX I

I.1 The Method of Calculating Dynamic Young's Modulus

Elastic theory gives the following relationship between the velocity of propagation of the standing wave and the wavelength of a rod of length L:

$$V = 2nL = K\sqrt{\frac{Ed}{\rho}}$$

where V = velocity of the standing wave (m/sec)

Ed = dynamic Young's modulus (GPa)

n = fundamental longitudinal resonant frequency (Hz)

L = length of rod (m)

ρ = mass density of the concrete or mortar specimen (kg/m^3)

K = a constant which depends on the units of measurement
= $10^{9/2}$ for the units illustrated above.

Hence;

$$Ed = 4 \times 10^{-9} n^2 L^2 \rho$$

For the calculation of the dynamic Young's modulus the values of n and L were determined as described in PART II, CHAPTER 3 and CHAPTER 4. The mass density, ρ, was calculated for each test specimen from the mass determination and the measurement of the specimen length (the width and depth of test specimens are constants).

It should be noted that for specimens which underwent drying, the dry mass was used in calculating dynamic Young's modulus: for test specimens re-immersed in water after drying, the mass of test specimens after re-immersion was used to calculate the dynamic Young's modulus.

I.2 The Method of Calculating Poisson's Ratio

Poisson's ratio was calculated from the measured values of dynamic Young's modulus and ultrasonic pulse velocity:

$$V = K\sqrt{\frac{Ed\ (1-\sigma)}{\rho(1+\sigma)(1-2\sigma)}} \quad m/sec$$

where V = velocity of wave propagation i.e. the ultrasonic pulse velocity (m/sec)

Ed = dynamic Young's modulus (GPa)

ρ = mass density of the concrete or mortar test specimen (kg/m^3)

K = a constant which depends on the units of measurement = $10^{9/2}$ for the units illustrated above.

σ = Poisson's ratio.

Hence;

$$\frac{(1+\sigma)(1-2\sigma)}{1-\sigma} = \frac{Ed \times 10^9}{V^2\rho}$$

The pulse velocity was determined using the apparatus described in PART II, CHAPTER 4, and Ed was calculated as described in APPENDIX I.1 above. The mass density of test specimens was calculated from the mass and length determinations (the width and depth of test speciments are constants). Consequently, the above quadratic equation could be solved for Poisson's ratio.

I.3 Calibration of the Linear Deformation Measuring Apparatus (attached to Furnace No. 1 and Waterbath No. 1)

The calibration of the apparatus used to measure linear deformation of heated test specimens was checked by measuring the linear expansion of a stainless steel bar of known thermal expansion. The stainless steel bar was approximately of the same length as the concrete and mortar test specimens (270 mm.). Linear expansion of the bar * was determined for the temperature ranges 30°C - 100°C and 30°C - 300°C for the apparatus attached to Furnace No. 1, and the temperature ranges 30°C - 70°C and 30°C - 100°C for the apparatus attached to Waterbath No. 1. The average temperature of the bar was determined from six Cr/Al thermocouples attached to the surface of the bar at various positions.

It was found that the coefficient of thermal expansion of the stainless steel bar was determined to within 2,5% for the temperature range 30°C - 70°C and within 1% for the temperature range 30°C - 300°C. The large error in thermal expansion in the temperature range 30°C - 70°C is due to the fact that the thermocouples had an accuracy of only 1%.

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* This linear expansion was corrected for the extension of the silica rods which coupled the bar to the measuring apparatus (see APPENDIX I.5.1).

Consequently, for the temperature range $30^{o}C$ - $70^{o}C$, the percentage error in temperature measurement is

$$\frac{70}{1} \times \frac{1}{100} + \frac{30}{1} \times \frac{1}{100}$$

$$= \underline{1,0^{o}C}$$

The possible percentage error in determining the temperature difference is

$$\frac{1.0}{(70-30)} \times \frac{100}{1}$$

$$= \underline{2,5\%}$$

In the above calibration tests the linear deformation of the steel bar was monitored for a total heating period of 48 hours. It was found that during this time period the linear deformation did not vary by more than 1%. This variation is probably due to the error in temperature control since the temperature controllers had an accuracy of approximately 1% of the set temperature.

I.4 The Method of Calculating the Total Water Content, W_t, the Water in the Capillary Pores, W_c, the water in the Gel Pores, W_g, and the Chemically Combined Water, W_n.

The total water content of test specimens prior to heating is greater than the water content of test specimens at mixing. This is because the test specimens were fully saturated during curing, i.e. water can be imbibed as some of the capillaries became emptied during hydration.

If C is the mass of cement and W the mass of water per test specimen, M the degree of hydration, and the specific gravity of cement taken as 3,15:

(i) W_n = chemically combined water[82]
$= \underline{0,23\ CM}$

(ii) W_g = water in the gel pores[82]
$= 0,28$ volume of gel

The volume of gel particles[82]

$$= \left[\frac{CM}{3,15} + \frac{0,23\ CM \times 0,746}{1}\right]$$

$$= 0,49\ CM$$

$$\therefore\ W_g = \underline{0,19\ CM}$$

(iii) W_c = water in the capillary pores
= volume of the capillary pores (since these are completely filled with water)
= total volume of cement and water at mixing - the volume of unhydrated cement - the volume of gel

$$= \left[\frac{C}{3,15} + W\right] - \left[\frac{C}{3,15}(1-M)\right] - \left[0,19\ CM + 0,49\ CM\right]$$

$$\therefore\ W_c = \underline{C\left[W/C - 0,36\ M\right]}$$

Consequently:

W_t = total water content after water curing
= $0,23\ CM + 0,19\ CM + C[W/C - 0,36\ M]$

where:

$W_n = 0,23\ CM$
= chemically combined water

$W_g = 0,19\ CM$
= water in the gel pores

$W_c = C[W/C - 0,36]$
= water in the capillary pores

In the above expansions the values of C, W/C and M are needed in order to calculate W_t, W_n, W_g and W_c:

(i) C is the weight of cement per test specimen and can be calculated from the mix proportions, the yeild of the particular mix and the volume of the test specimens.

(ii) W/C is the water cement ratio which is known.

(iii) M = degree of hydration after 28 days moist curing at 21^oC
= 72,3% *.

Consequently, the values of W_t, W_n, W_g and W_c may be calculated for the various concrete and mortar mixes.

(83,84)

* Calculated from experimental determinations of W_n after 28 days moist curing

I.5.1 Corrections to the Linear Deformation Curves for Extension of the Silica Rods

The small extension of the silica rods which coupled the linear deformation test specimens to the dial gauge/l.v.d.t. apparatus had to be taken into account in determining the linear expansion curves of heated test specimens.

In preliminary heating tests the temperature distribution along the total length of silica rods (within the furnace as well as outside the furnace) was determined by attaching thermocouples at short intervals along the surface of the silica rods. For the various test temperatures the average temperature of the silica rods was thus determined. Consequently, the average extension of the silica rods at the various test temperatures could be calculated. This extension was subtracted from the linear deformation curves of the concrete and mortar test specimens.

Corrections to the Linear Deformation Curves for Small Fluctuations of the Test Specimen Average Temperature about the Test Temperature

In some instances the average temperature of test specimens was not exactly equal to the test temperature level. This is because the temperature controllers had an accuracy of only 1% of the set temperature. The linear deformation curves were corrected for these deviations from the test temperature i.e. the curves were adjusted to show the linear deformation which would have occurred if the test specimen average temperature was equal to the test temperature.

The adjustment was done by:

(i) the coefficient of thermal expansion was calculated from the value of linear deformation and temperature difference that occurred at the time when the desired temperature level was attained (i.e. the coefficient of thermal expansion was calculated on the assumption that no residual deformation of the test specimen had occurred at this time).

(ii) the coefficient of thermal expansion was calculated from the change in linear deformation and temperature change that occurred during the first cooling cycle (i.e. the residual linear deformation was taken into account).

Consequently, correction to the linear deformation curve could be applied

at points corresponding to (i) and (ii) above. Intermediate values were adjusted by interpolating between the values determined from (i) and (ii) above.

APPENDIX II

Tabulated results of residual linear deformation, water loss compressive strength, ultrasonic pulse velo ity, dynamic Young's modulus and Poisson's ratio of concrete and mortar specimens at the various temperature levels.

(i) Table A.II.1 to Table A.II.7 : Mix BCY	}	CONCRETE MIXES
(ii) Table A.II.8 to Table A.II.14: Mix CCX		
(iii) Table A.II.15 to Table A.II.21: Mix CCY		
(iv) Table A.II.22 to Table A.II.28: Mix BMY	}	MORTAR MIXES
(v) Table A.II.29 to Table A.II.35: Mix CMX		
(vi) Table A.II.36 to Table A.II.42: Mix CMY		

For each of (i) to (vi) above the data for the tests performed at the different temperature levels is given in the following order:
70 ^{o}C (fully saturated); 100 ^{o}C (fully saturated); 70 ^{o}C (dry); 100 ^{o}C (dry); 150 ^{o}C (dry); 250 ^{o}C (dry); 400 ^{o}C (dry).

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

SPECIMEN SERIES : BCY

TEMPERATURE : 70°C

TREATMENT : SATURATED DURING HEATING

INITIAL WATER CONTENT = 304 g = W_t

VIZ. W_c = 134 g = 44,1%

W_n = 93 g = 30,6%

W_g = 72 g = 25,3%

Spec. No.	DEFORMATION			COMPRESSIVE STRENGTH			WATER LOSS					HEAT TREATMENT
	Initial length mm	Strain ** mm/m	Strain *** mm/m	MPa	R.R %		Mass before heat A(g)	Mass after heat B(g)	$\frac{A-B}{W_t}$ %	Mass after wett. C(g)	$\frac{A-C}{W_t}$ %	
1	272,3			51,08			3915					No Heating.
2	273,1			48,75			3994					Tested at
3	273,1			50,73			3946					Room Temp.
Mean 1,2,3	272,9			50,19			3952					
4				45,65	89,7	*						Tested Imm. Max. Temp. Attained (Time T)
5	271,3	0,03		47,72	93,8	**	3959	3959	0,0			
6	273,6	0,04	0,03	50,04	98,3	***	4021	4020	0,30	4023	-0,7	
7				45,30	89,0	*						Tested At T + 12 hrs
8	273,1	0,04		47,80	93,9	**	4008	4007	0,30			
9	271,3	0,05	0,03	50,56	99,3	***	3980	3977	1,00	3979	0,3	
10				45,48	89,4	*						Tested At T + 24 hrs
11	272,3	0,05		48,06	94,4	**	3913	3916	-1,00			
12	272,0	0,06	0,05	49,61	97,5	***	3934	3932	0,70	3935	-0,3	
13				45,70	89,8	*						Tested At T + 36 hrs
14	272,5	0,06		47,63	93,6	**	3964	3962	0,70			
15	272,0	0,07	0,06	50,56	99,3	***	3943	3941	0,70	3944	-0,3	
16				44,79	88,0	*						Tested At T + 36 hrs + 1 cycle
17	273,6	0,07		48,15	94,6	**	3926	3924	0,7			
18	272,5	0,07	0,06	47,37	93,1	***	3989	3987	0,7	3990	-0,3	
19				46,08	90,5	*						Tested At T + 36 hrs + 2 Cycles
20	271,3	0,06		47,97	94,2	**	3883	3880	1,0			
21	272,5	0,05	0,05	48,15	94,6	***	3968	3964	1,3	3967	0,3	
22						*						Tested At T + 36 hrs + 2 Cycles
23	271,5	0,07		49,18		**	3981	3972	3,0			
24	273,6	0,04	0,04	53,06		***	3981	3979	0,7	3982	-0,3	
Mean 1-24	272,3						3961					

* TESTED HOT

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE A.II.1

SPECIMEN SERIES : BCY

TEMPERATURE : 70°C

TREATMENT : SATURATED DURING HEATING

Spec. No.	PULSE VELOCITY				DYNAMIC YOUNG'S MODULUS				POISSON'S RATIO			
	* m/sec	** and *** m/sec	R.R %		* GPa	** and *** GPa	R.R %		*	** and ***	R.R %	
1	4792				37,69				0,335			
2	4704				38,32				0,325			
3	4675				38,54				0,316			
Mean of 1,2,3	4724				38,18				0,325			
4												
5	4792	4675	98,0	**	38,37	37,11	92,8	**	0,334	0,330	104,4	**
6	4704	4704	98,6	***	39,44	38,91	97,3	***	0,318	0,322	101,9	***
7												
8	4618	4590	96,2	**	38,69	37,06	92,6	**	0,312	0,321	101,6	**
9	4675	4675	98,0	***	39,25	38,70	96,7	***	0,315	0,319	100,9	***
10												
11	4733	4675	98,0	**	36,87	36,12	90,3	**	0,334	0,331	104,7	**
12	4704	4733	99,2	***	38,37	37,85	94,6	***	0,321	0,329	104,1	***
13												
14	4733	4675	98,0	**	38,73	35,74	89,3	**	0,324	0,339	107,3	**
15	4675	4733	99,2	***	38,86	38,16	95,4	***	0,314	0,327	103,5	***
16												
17	4675	4646	97,4	**	37,83	35,87	89,7	**	0,320	0,331	104,7	**
18	4704	4704	98,6	***	39,52	38,32	95,8	***	0,316	0,325	102,8	***
19												
20	4733	4733	99,2	**	36,46	35,76	89,4	**	0,336	0,341	107,9	**
21	4675	4704	98,6	***	39,36	38,63	96,6	***	0,312	0,321	101,6	***
22												
23	4704	4646		**	39,57	3761		**	0,316	0,323		**
24	4646	4646		***	37,22	37,70		***	0,325	0,321		***
Mean of 1-24	4699				38,47				0,321			

* TESTED BEFORE HEATING

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE A.II.1 (contd.)

SPECIMEN SERIES : BCY

TEMPERATURE : 100°C

TREATMENT : SATURATED DURING HEATING

INITIAL WATER CONTENT = 304 g = W_t

VIZ. W_c = 134 g = 44,1%
W_n = 93 g = 30,6%
W_g = 77 g = 25,3%

Spec. No.	DEFORMATION			COMPRESSIVE STRENGTH			WATER LOSS					HEAT TREATMENT
	Initial length mm	Strain ** mm/m	Strain *** mm/m	MPa	R.R %		Mass before heat A(g)	Mass after heat B(g)	$\frac{A-B}{W_t}$ %	Mass after wett. C(g)	$\frac{A-C}{W_t}$ %	
1	271,3			53,06			3905					No Heating.
2	273,3			51,08			3900					Tested at
3	268,7			53,49			3896					Room Temp.
Mean 1,2,3	271,3			52,54			3900					
4				40,22	79,0	*						Tested Imm.
5	272,5	0,03		41,77	82,1	**	3960	3956	1,3			Max. Temp.
6	273,3	0,04	0,03	45,91	90,2	***	3932	3927	1,6	3932	0,0	Attained (Time T)
7				40,31	79,2	*						Tested At
8	270,3	0,04		40,57	79,7	**	3852	3847	1,6			T + 12 hrs
9	270,5	0,05	0,03	45,99	90,4	***	3901	3896	1,6	3900	+0,3	
10				42,89	84,3	*						Tested At
11	273,1	0,05		44,18	86,8	**	3893	3889	1,3			T + 24 hrs
12	270,3	0,06	0,05	46,17	90,7	***	3826	3821	1,6	3826	0,0	
13				42,81	84,1	*						Tested At
14	272,0	0,06		45,82	90,0	**	3896	3891	1,6			T + 36 hrs
15	275,1	0,07	0,06	47,03	92,4	***	3961	3975	1,3	3962	-0,3	
16				44,53	87,5	*						Tested At
17	271,3	0,07		47,54	93,4	**	3914	3909	1,6			T + 36 hrs
18	275,1	0,07	0,06	48,23	94,8	***	3974	3970	1,3	3975	-0,3	+ 1 cycle
19				43,93	86,3	*						Tested At
20	273,3	0,06		48,41	95,1	**	3940	3935	1,6			T + 36 hrs
21	271,8	0,05	0,05	48,58	95,4	***	3961	3958	1,0	3963	-0,7	+ 2 Cycles
22						*						Tested At
23	274,8	0,07		46,42		**	3966	3955	3,6			T + 36 hrs
24	271,5	0,04	0,04	47,97		***	3894	3888	2,0	3893	+0,3	+ 2 Cycles
Mean 1-24	272,5						3919					

* TESTED HOT

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE A.II.2

SPECIMEN SERIES : BCY

TEMPERATURE : 100°C

TREATMENT : SATURATED DURING HEATING

Spec. No.	PULSE VELOCITY				DYNAMIC YOUNG'S MODULUS				POISSON'S RATIO			
	* m/sec	** and *** m/sec	R.R %		* GPa	** and *** GPa	R.R %		*	** and ***	R.R %	
1	4674				38,62				0,314			
2	4792				38,35				0,328			
3	4703				39,20				0,315			
Mean of 1,2,3	4724				38,72				0,319			
4												
5	4763	4646	97,4	**	38,74	35,95	89,9	**	0,327	0,334	105,7	**
6	4733	4618	96,8	***	37,97	35,93	89,5	***	0,326	0,328	103,8	***
7												
8	4792	4618	96,8	**	37,33	34,00	85,0	**	0,335	0,340	107,6	**
9	4792	4618	96,8	***	39,19	36,81	92,0	***	0,325	0,322	101,9	***
10												
11	4763	4590	96,2	**	37,86	33,71	84,3	**	0,328	0,339	107,3	**
12	4792	4704	98,6	***	38,71	35,60	89,0	***	0,323	0,336	106,3	***
13												
14	4763	4646	97,4	**	37,35	35,04	87,6	**	0,333	0,336	106,3	**
15	4792	4563	95,6	***	38,29	36,18	90,4	***	0,331	0,319	100,9	***
16												
17	4733	4646	97,4	**	39,14	35,46	88,7	**	0,318	0,335	106,0	**
18	4763	4646	97,4	***	38,27	36,67	91,7	***	0,329	0,327	103,5	***
19												
20	4792	4646	97,4	**	38,62	35,60	89,0	**	0,329	0,334	105,7	**
21	4792	4675	98,0	***	38,61	37,09	92,7	***	0,332	0,330	104,4	***
22												
23	4763	4646		**	38,05	35,55		**	0,330	0,334		**
24	4792	4704		***	38,41	36,88		***	0,329	0,330		***
Mean of 1-24	4773				38,32				0,328			

* TESTED BEFORE HEATING

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE A.II.2 (contd.)

SPECIMEN SERIES : BCY

TEMPERATURE : 70°C

TREATMENT : DRYING DURING HEATING

INITIAL WATER CONTENT = 304 g = W_t

VIZ. W_c = 134 g = 44,1%

W_n = 93 g = 30,6%

W_g = 77 g = 25,3%

Spec. No.	DEFORMATION			COMPRESSIVE STRENGTH			WATER LOSS					HEAT TREATMENT
	Initial length mm	Strain ** mm/m	Strain *** mm/m	MPa	R.R %		Mass before heat A(g)	Mass after heat B(g)	$\frac{A-B}{W_t}$ %	Mass after wett. C(g)	$\frac{A-C}{W_t}$ %	
1	271,1			50,95			3921					No Heating.
2	272,5			52,08			3982					Tested at
3	273,3			48,85			3902					Room Temp.
Mean 1,2,3	272,3			50,63			3935					
4				47,88	94,1	*						Tested Imm.
5	272,8	-0,15		56,72	111,4	**	3991	3930	20,1			Max. Temp.
6	271,5	-0,17	-0,03	49,9	98,0	***	4002	3945	18,8	3989	4,3	Attained (Time T)
7				46,57	91,5	*						Tested At
8	270,5	-0,15		52,79	103,7	**	3930	3854	25,0			T + 12 hrs
9	270,3	-0,17	0,02	50,60	99,4	***	3915	3832	27,3	3907	2,6	
10				49,37	97,0	*						Tested At
11	270,8	-0,19		52,87	103,9	**	3941	3850	29,9			T + 24 hrs
12	274,3	-0,19	-0,03	45,87	90,1	***	3966	3873	30,6	3955	3,6	
13				49,55	97,3	*						Tested At
14	270,5	-0,23		54,80	107,7	**	3902	3794	35,5			T + 36 hrs
15	271,5	-0,21	-0,04	49,72	97,7	***	3911	3809	33,6	3899	3,9	
16				52,35	102,8	*						Tested At
17	273,3	-0,21		55,67	109,4	**	3900	3778	36,8			T + 36 hrs
18	271,8	-0,20	-0,03	46,48	91,3	***	3921	3815	34,9	3912	3,0	+ 1 cycle
19				53,66	105,4	*						Tested At
20	270,5	-0,21		53,57	105,2	**	3917	3821	34,9			T + 36 hrs
21	272,8	-0,21	-0,05	48,06	94,4	***	3982	3880	33,5	3971	3,6	+ 2 Cycles
22						*						Tested At
23	273,3	-0,20		55,15		**	3898	3771	41,8			T + 36 hrs
24	273,1	-0,20	-0,01	45,52		***	3890	3772	38,8	3880	3,3	+ 2 Cycles
Mean 1-24	272,0						3934					

* TESTED HOT

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE.A.II.3

SPECIMEN SERIES : BCY

TEMPERATURE : 70°C

TREATMENT : DRYING DURING HEATING

Spec. No.	PULSE VELOCITY				DYNAMIC YOUNG'S MODULUS				POISSON'S RATIO			
	* m/sec	** and *** m/sec	R.R %		* GPa	** and *** GPa	R.R %		*	** and ***	R.R %	
1	4792				38,43				0,331			
2	4822				39,11				0,333			
3	4822				40,60				0,315			
Mean of 1,2,3	4813				39,38				0,327			
4												
5	4792	4675	98,0	**	40,75	38,95	97,4	**	0,318	0,311	98,4	**
6	4792	4704	98,6	***	42,36	40,55	101,4	***	0,308	0,309	97,8	***
7												
8	4822	4675	98,0	**	41,44	37,98	94,9	**	0,314	0,316	100,0	**
9	4885	4762	99,8	***	40,53	38,68	96,7	***	0,328	0,326	103,2	***
10												
11	4822	4675	98,0	**	40,88	36,73	91,8	**	0,319	0,325	102,8	**
12	4853	4704	98,6	***	38,71	38,61	96,5	***	0,336	0,318	100,6	***
13												
14	4792	4563	95,6	**	36,93	35,81	89,5	**	0,341	0,314	99,4	**
15	4762	4646	97,4	***	38,73	37,67	94,2	***	0,324	0,317	100,3	***
16												
17	4853	4618	96,8	**	40,34	36,23	90,6	**	0,321	0,314	99,4	**
18	4792	4704	98,6	***	39,57	38,36	95,9	***	0,322	0,320	101,3	***
19												
20	4762	4675	98,0	**	40,53	36,27	90,7	**	0,313	0,327	103,5	**
21	4732	4704	98,6	***	41,28	39,46	98,6	***	0,305	0,315	99,7	***
22												
23	4762	4618		**	38,70	34,80		**	0,322	0,325		**
24	4792	4675		***	38,85	36,97		***	0,324	0,323		***
Mean of 1-24	4800				39,97				0,315			

* TESTED BEFORE HEATING

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE A.II.3 (contd.)

SPECIMEN SERIES : BCY

TEMPERATURE : 100°C

TREATMENT : DRYING DURING HEATING

INITIAL WATER CONTENT = 304 g = W_t

VIZ. W_c = 134 g = 44,1%; W_n = 93 g = 30,6%; W_g = 77 g = 25,3%

Spec. No.	DEFORMATION			COMPRESSIVE STRENGTH		WATER LOSS					HEAT TREATMENT
	Initial length mm	Strain ** mm/m	Strain *** mm/m	MPa	R.R %	Mass before heat A(g)	Mass after heat B(g)	$\frac{A-B}{W_t}$ %	Mass after wett. C(g)	$\frac{A-C}{W_t}$ %	
1	270,4			49,27		3954					No Heating.
2	272,3			50,30		3906					Tested at
3	273,0			44,96		3951					Room Temp.
Mean 1,2,3	271,9			49,79		3937					
4				42,38	83,3 *						Tested Imm.
5	271,3	-0,14		45,13	88,7 **	3915	3799	38,2			Max. Temp.
6	273,3	-0,14	+0,03	41,00	80,6 ***	4025	3922	33,9	4014	3,6	Attained (Time T)
7				44,01	86,5 *						Tested At
8	272,0	-0,19		45,65	89,7 **	3951	3793	52,0			T + 12 hrs
9	272,5	-0,23	-0,07	39,10	76,8 ***	3937	3766	56,3	3922	4,9	
10				45,65	89,7 *						Tested At
11	273,1	-0,24		46,25	90,9 **	3985	3818	54,9			T + 24 hrs
12	272,0	-0,24	-0,07	37,98	74,6 ***	3951	3784	54,9	3939	3,9	
13				52,19	102,5 *						Tested At
14	272,5	-0,27		49,78	97,8 **	3983	3812	56,3			T + 36 hrs
15	271,5	-0,29	-0,12	41,51	81,6 ***	3940	3766	57,2	3924	5,3	
16				45,82	90,0 *						Tested At
17	272,0	-0,26		47,84	94,0 **	4002	3831	56,3			T + 36 hrs
18	271,5	-0,30	-0,12	37,21	73,1 ***	3900	3721	58,9	3886	4,6	+ 1 cycle
19				48,75	95,8 *						Tested At
20	271,8	-0,27		49,96	98,2 **	3977	3806	56,3			T + 36 hrs
21	273,1	-0,24	-0,07	36,26	71,2 ***	4001	3833	55,3	3987	4,6	+ 2 Cycles
22					*						Tested At
23	272,0	-0,30		49,27	**	3979	3794	60,9			T + 36 hrs
24	270,8	-0,28	-0,09	38,59	***	3949	3760	62,2	3933	5,3	+ 2 Cycles
Mean 1-24	272,0					3964					

* TESTED HOT

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE.A.II.4

SPECIMEN SERIES : BCY

TEMPERATURE : 100°C

TREATMENT : DRYING DURING HEATING

Spec. No.	PULSE VELOCITY				DYNAMIC YOUNG'S MODULUS				POISSON'S RATIO			
	* m/sec	** and *** m/sec	R.R %		* GPa	** and *** GPa	R.R %		*	** and ***	R.R %	
1	4822				42,26				0,310			
2	4853				43,04				0,301			
3	4732				42,76				0,288			
Mean of 1,2,3	4802				42,69				0,300			
4												
5	4732	4536	95,1	**	41,40	34,61	86,5	**	0,299	0,321	101,6	**
6	4762	4618	96,8	***	44,14	41,35	103,4	***	0,288	0,288	91,1	***
7												
8	4732	4354	91,2	**	40,73	34,85	87,1	**	0,307	0,289	91,5	**
9	4792	4590	96,2	***	42,90	37,42	93,5	***	0,297	0,313	99,1	***
10												
11	4823	4430	92,8	**	43,32	35,87	89,7	**	0,303	0,294	93,0	**
12	4703	4456	93,4	***	42,79	37,65	94,1	***	0,285	0,291	92,1	***
13												
14	4792	4404	92,3	**	43,05	35,54	88,8	**	0,299	0,291	92,1	**
15	4762	4618	96,8	***	43,21	38,17	95,4	***	0,299	0,311	98,4	***
16												
17	4792	4404	92,3	**	42,59	34,50	86,2	**	0,305	0,305	96,5	**
18	4675	45,36	95,1	***	42,16	37,34	93,3	***	0,281	0,303	95,9	***
19												
20	4762	4379	91,8	**	43,37	35,59	89,0	**	0,292	0,287	90,8	**
21	4703	4509	94,5	***	42,58	37,93	94,8	***	0,290	0,300	94,9	***
22												
23	4732	4330		**	43,43	35,36		**	0,287	0,287		**
24	4703	4456		***	41,84	36,69		***	0,295	0,302		***
Mean of 1-24	4748				42,60				0,295			

* TESTED BEFORE HEATING

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE A.II.4 (contd.)

SPECIMEN SERIES : BCY

TEMPERATURE : 150°C

TREATMENT : DRYING DURING HEATING

INITIAL WATER CONTENT = 304 g = W_t

VIZ. W_c = 134 g = 44,1%

W_n = 93 g = 30,6%

W_g = 77 g = 25,3%

Spec. No.	DEFORMATION			COMPRESSIVE STRENGTH			WATER LOSS					HEAT TREATMENT
	Initial length mm	Strain ** mm/m	Strain *** mm/m	MPa	R.R %		Mass before heat A(g)	Mass after heat B(g)	$\frac{A-B}{W_t}$ %	Mass after wett. C(g)	$\frac{A-C}{W_t}$ %	
1	272,8			51,69			3952					No Heating.
2	270,4			50,64			3911					Tested at
3	271,3			52,80			3924					Room Temp.
Mean 1,2,3	271,5			51,71			3929					
4				46,95	92,0	*						Tested Imm.
5	272,0	-0,13		46,94	92,2	**	3909	3735	57,2			Max. Temp.
6	273,1	-0,13	0,0	3936	77,3	***	3932	3757	57,6	3919	4,3	Attained (Time T)
7				53,57	105,6	*						Tested At
8	270,3	-0,23		56,16	110,3	**	3897	3697	65,8			T + 12 hrs
9	271,8	-0,24	0,0	39,28	77,2	***	3899	3672	74,7	3882	5,6	
10				52,88	103,9	*						Tested At
11	273,6	-0,26		57,19	112,4	**	3994	3785	68,8			T + 24 hrs
12	272,0	-0,27	-0,02	39,62	77,8	***	3953	3744	68,8	3936	5,6	
13				54,00	106,1	*						Tested At
14	272,3	-0,27		53,06	104,2	**	3957	3739	71,7			T + 36 hrs
15	272,3	-0,26	-0,01	38,24	75,1	***	3929	3716	70,1	3912	5,6	
16				57,02	112,0	*						Tested At
17	273,3	-0,30		55,04	108,1	**	3960	3740	72,4			T + 36 hrs
18	273,3	-0,27	-0,01	40,31	79,2	***	4020	3822	65,1	4008	3,9	+ 1 cycle
19				55,98	110,0	*						Tested At
20	271,8	-0,26		60,03	117,9	**	3924	3720	67,1			T + 36 hrs
21	271,5	-0,28	-0,01	40,65	79,9	***	3907	3693	70,4	3890	5,6	+ 2 Cycles
22						*						Tested At
23	270,8	-0,28		55,90		**	3929	3701	75,0			T + 36 hrs
24	272,3	-0,29	-0,02	38,76		***	3895	3684	69,4	3880	4,9	+ 2 Cycles
Mean 1-24	272,3						3936					

* TESTED HOT

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE A.II.5

SPECIMEN SERIES : BCY

TEMPERATURE : 150°C

TREATMENT : DRYING DURING HEATING

Spec. No.	PULSE VELOCITY				DYNAMIC YOUNG'S MODULUS				POISSON'S RATIO			
	* m/sec	** and *** m/sec	R.R %		* GPa	** and *** GPa	R.R %		*	** and ***	R.R %	
1	4762				40,41				0,313			
2	4792				39,06				0,327			
3	4792				40,11				0,319			
Mean of 1,2,3	4782				39,86				0,320			
4												
5	4916	4509	94,5	**	39,49	31,91	79,8	**	0,336	0,335	106,0	**
6	4732	4456	93,4	***	38,47	34,96	87,4	***	0,322	0,314	99,4	***
7												
8	4885	4281	89,7	**	40,37	31,61	79,0	**	0,327	0,305	96,5	**
9	4762	4379	91,8	***	37,97	32,35	80,9	***	0,329	0,325	102,8	***
10												
11	4885	4257	89,2	**	40,02	31,37	78,4	**	0,333	0,308	97,5	**
12	4853	4456	93,4	***	40,59	34,53	86,3	***	0,324	0,320	101,3	***
13												
14	4732	4257	89,2	**	39,04	29,65	74,1	**	0,321	0,323	102,2	**
15	4792	4482	93,9	***	39,40	33,25	83,1	***	0,323	0,332	105,1	***
16												
17	4853	4281	89,7	**	38,56	29,04	72,6	**	0,338	0,331	104,7	**
18	4792	4482	93,9	***	41,25	35,79	89,5	***	0,316	0,317	100,3	***
19												
20	4853	4281	89,7	**	40,31	30,82	77,0	**	0,324	0,314	99,4	**
21	4792	4456	93,4	***	38,54	32,87	82,2	***	0,329	0,332	105,1	***
22												
23	4703	4164		**	40,81	29,59		**	0,302	0,308		**
24	4762	4456		***	38,53	33,42		***	0,324	0,325		***
Mean of 1-24	4808				39,53				0,324			

* TESTED BEFORE HEATING

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE A.II.5 (contd.)

SPECIMEN SERIES : BCY

TEMPERATURE : 250°C

TREATMENT : DRYING DURING HEATING

INITIAL WATER CONTENT = 304 g = W_t

VIZ. W_c = 134 g = 44,1%

W_n = 93 g = 30,6%

W_g = 77 g = 25,3%

Spec. No.	DEFORMATION			COMPRESSIVE STRENGTH			WATER LOSS					HEAT TREATMENT
	Initial length mm	Strain ** mm/m	Strain *** mm/m	MPa	R.R %		Mass before heat A(g)	Mass after heat B(g)	$\frac{A-B}{W_t}$ %	Mass after wett. C(g)	$\frac{A-C}{W_t}$ %	
1	271,4			49,27			3946					No Heating. Tested at Room Temp.
2	270,9			49,70			3917					
3	271,0			46,51			3927					
Mean 1,2,3	271,1			48,5			3930					
4				50,99	100,2	*						Tested Imm. Max. Temp. Attained (Time T)
5	271,5	-0,07		43,93	86,3	**	3950	3728	73,0			
6	270,0	-0,10	+0,29	37,04	72,8	***	3948	3725	73,4	3937	3,6	
7				50,99	100,2	*						Tested At T + 12 hrs
8	272,0	-0,13		45,99	90,4	**	3946	3721	74,0			
9	270,5	-0,11	+0,34	36,86	72,4	***	3941	3715	74,3	3927	4,6	
10				49,27	96,8	*						Tested At T + 24 hrs
11	270,8	-0,15		46,17	90,7	**	3946	3137	68,8			
12	272,3	-0,17	+0,34	37,72	72,8	***	3872	3639	76,6	3859	4,3	
13				48,92	96,1	*						Tested At T + 36 hrs
14	271,5	-0,18		46,17	90,7	**	3906	3689	71,4			
15	270,8	-0,20	+0,33	37,04	72,8	***	3947	3728	72,0	3939	2,6	
16				49,09	96,4	*						Tested At T + 36 hrs + 1 cycle
17	268,2	-0,16		49,44	97,1	**	3920	3700	72,4			
18	270,0	-0,17	+0,38	38,24	75,1	***	3951	3741	69,1	3942	3,0	
19				48,96	96,2	*						Tested At T + 36 hrs + 2 Cycles
20	273,1	-0,20		46,95	92,2	**	3988	3778	69,1			
21	271,3	-0,20	+0,32	38,27	75,2	***	3883	3663	72,4	3874	3,0	
22						*						Tested At T + 36 hrs + 2 Cycles
23	270,3	-0,24		45,48		**	3802	3581	72,7			
24	270,0	-0,24	+0,32	39,10		***	3814	3582	76,3	3802	3,9	
Mean 1-24	270,8						3916					

* TESTED HOT

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE A.II.6

SPECIMEN SERIES : BCY

TEMPERATURE : 250°C

TREATMENT : DRYING DURING HEATING

Spec. No.	PULSE VELOCITY				DYNAMIC YOUNG'S MODULUS				POISSON'S RATIO			
	* m/sec	** and *** m/sec	R.R %		* GPa	** and *** GPa	R.R %		*	** and ***	R.R %	
1	4792				40,94				0,314			
2	4792				40,21				0,318			
3	4792				40,74				0,315			
Mean of 1,2,3	4792				40,63				0,316			
4												
5	4792	3829	80,2	**	41,47	17,83	44,6	**	0,310	0,386	122,2	**
6	4823	4482	93,9	***	41,55	36,21	90,5	***	0,315	0,312	98,7	***
7												
8	4885	3948	82,7	**	41,32	18,69	46,7	**	0,308	0,388	122,8	**
9	4792	4509	94,5	***	41,55	36,08	90,2	***	0,310	0,309	97,8	***
10												
11	4854	4011	84,1	**	41,31	19,39	48,5	**	0,320	0,388	122,8	**
12	4823	4590	96,2	***	39,47	36,05	90,1	***	0,322	0,310	98,1	***
13												
14	4792	3829	80,2	**	41,26	18,78	46,9	**	0,308	0,376	119,0	**
15	4823	4563	95,6	***	40,28	37,06	92,6	***	0,324	0,315	99,7	***
16												
17	4763	3829	80,2	**	41,86	18,56	46,4	**	0,305	0,380	120,3	**
18	4823	4563	95,6	***	41,58	38,03	95,1	***	0,315	0,308	97,5	***
19												
20	4885	3937	82,5	**	42,44	18,21	45,5	**	0,316	0,388	122,8	**
21	4792	4509	94,5	***	39,70	36,37	90,9	***	0,319	0,310	98,1	***
22												
23	4823	4011		**	40,21	18,70		**	0,314	0,388		**
24	4763	4590		***	39,50	35,12		***	0,313	0,325		***
Mean of 1-24	4815				40,98				0,314			

* TESTED BEFORE HEATING

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE A.II.6 (contd.)

SPECIMEN SERIES : BCY

TEMPERATURE : 400°C

TREATMENT : DRYING DURING HEATING

INITIAL WATER CONTENT = 304 g = W_t

VIZ. W_c = 134 g = 44,1%

W_n = 93 g = 30,6%

W_g = 77 g = 25,3%

Spec. No.	DEFORMATION			COMPRESSIVE STRENGTH			WATER LOSS					HEAT TREATMENT
	Initial length mm	Strain ** mm/m	Strain *** mm/m	MPa	R.R %		Mass before heat A(g)	Mass after heat B(g)	$\frac{A-B}{W_t}$ %	Mass after wett. C(g)	$\frac{A-C}{W_t}$ %	
1	272,0			53,75			3927					No Heating. Tested at Room Temp.
2	271,4			53,06			3931					
3	273,2			51,68			3902					
Mean 1,2,3	272,2			52,81			3920					
4				43,58	85,6	*						Tested Imm. Max. Temp. Attained (Time T)
5	273,6	0,58		40,31	79,2	**	3923	3659	86,8			
6	271,3	0,59	1,46	37,38	73,4	***	3929	3683	80,9	3921	2,6	
7				49,09	96,4	*						Tested At T + 12 hrs
8	272,5	0,41		40,65	79,9	**	3948	3709	78,6			
9	272,5	1,69	2,50	37,98	74,6	***	3981	3721	85,5	3978	1,0	
10				49,52	97,3	*						Tested At T + 24 hrs
11	272,5	0,93		38,33	75,3	**	3898	3630	88,2			
12	272,0	0,56	1,30	37,90	74,5	***	3881	3621	84,5	3871	3,3	
13				46,60	91,6	*						Tested At T + 36 hrs
14	271,8	1,41		36,86	72,4	**	3878	3612	87,5			
15	271,0	0,67	1,35	40,48	79,5	***	3935	3701	77,0	3929	2,0	
16				43,24	85,0	*						Tested At T + 36 hrs + 1 cycle
17	272,3	1,56		39,62	77,8	**	3923	3667	84,2			
18	272,8	0,96	2,00	39,96	78,5	***	3935	3680	83,9	3931	1,3	
19				47,46	93,2	*						Tested At T + 36 hrs + 2 Cycles
20	271,3	0,61		42,55	83,6	**	3902	3649	83,2			
21	272,3	0,48	1,17	43,93	86,3	***	3881	3635	80,9	3871	3,3	
22						*						Tested At T + 36 hrs + 2 Cycles
23	271,3	0,93		42,55		**						
24	271,0	0,70	1,40	35,66		***	3906	3654	82,9	3902	1,3	
Mean 1-24	272,0						3916					

* TESTED HOT

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE A.II.7

SPECIMEN SERIES : BCY

TEMPERATURE : 400°C

TREATMENT : DRYING DURING HEATING

Spec. No.	PULSE VELOCITY				DYNAMIC YOUNG'S MODULUS				POISSON'S RATIO			
	* m/sec	** and *** m/sec	R.R %		* GPa	** and *** GPa	R.R %		*	** and ***	R.R %	
1	4885				41,63				0,319			
2	4854				41,58				0,311			
3	4733				39,59				0,311			
Mean of 1,2,3	4823				40,93				0,315			
4												
5	4733	3243	68,0	**	39,52	12,10	302,	**	0,313	0,390	123,4	**
6	4792	4430	92,6	***	39,76	31,17	77,9	***	0,322	0,344	108,9	***
7												
8	4763	3229	67,7	**	41,94	14,04	35,1	**	0,301	0,367	116,1	**
9	4823	4509	94,5	***	40,75	33,05	82,6	***	0,321	0,341	107,9	***
10												
11	4763	3000	62,9	**	38,49	10,91	27,3	**	0,324	0,381	120,6	**
12	4763	4430	92,8	***	39,53	32,68	81,7	***	0,316	0,328	103,8	***
13												
14	4733	2953	61,9	**	38,29	7,98	20,0	**	0,321	0,403	127,5	**
15	4854	4590	96,2	***	41,77	35,48	88,7	***	0,316	0,330	104,4	***
16												
17	4763	2761	57,9	**	39,67	7,85	19,6	**	0,317	0,404	127,8	**
18	4763	4563	95,6	***	40,96	34,48	86,2	***	0,308	0,333	105,4	***
19												
20	4704	2865	60,0	**	40,71	12,00	30,0	**	0,300	0,347	109,8	**
21	4763	4509	94,5	***	38,92	32,61	81,5	***	0,320	0,338	107,0	***
22												
23	4733			**	39,34	7,65		**	0,316			**
24	4704	4456		***	40,25	34,00		***	0,305	0,324		***
Mean of 1-24	4761				39,99				0,314			

* TESTED BEFORE HEATING

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE A.II.7 (contd.)

SPECIMEN SERIES : CCX

TEMPERATURE : 70°C

TREATMENT : SATURATED DURING HEATING

INITIAL WATER CONTENT = 338,5 g = W_t

VIZ. W_c = 174 g = 57,4%
W_n = 90 g = 26,6%
W_g = 74,5 g = 22,0%

Spec. No.	DEFORMATION			COMPRESSIVE STRENGTH			WATER LOSS					HEAT TREATMENT
	Initial length mm	Strain ** mm/m	Strain *** mm/m	MPa	R.R %		Mass before heat A(g)	Mass after heat B(g)	$\frac{A-B}{W_t}$ %	Mass after wett. C(g)	$\frac{A-C}{W_t}$ %	
1	270,5			35,92			3910					No Heating.
2	274,3			40,22			3966					Tested at
3	271,0			39,79			3867					Room Temp.
Mean 1,2,3	271,9			38,64			3914					
4				33,33	83,4	*						Tested Imm.
5	271,3	0,03		37,98	95,1	**	3865	3859	1,77			Max. Temp.
6	272,3	0,03	0,04	38,67	96,8	***	3930	3929	0,30	3930	0,0	Attained (Time T)
7				33,59	84,1	*						Tested At
8	272,3	0,06		33,33	83,4	**	3940	3937	0,89			T + 12 hrs
9	271,8	0,04	0,03	39,36	98,5	***	3912	3909	0,89	3909	0,89	
10				33,07	82,8	*						Tested At
11	271,8	0,09		34,19	85,6	**	3933	3930	0,89			T + 24 hrs
12	272,5	0,06	0,07	34,97	87,5	***	3972	3968	1,18	3969	0,89	
13				32,73	81,9	*						Tested At
14	271,0	0,08		35,74	89,5	**	3905	3901	1,18			T + 36 hrs
15	271,3	0,08	0,10	35,40	88,6	***	3937	3934	0,89	3934	0,89	
16				32,73	81,9	*						Tested At
17	272,3	0,09		35,31	88,4	**	3948	3944	1,18			T + 36 hrs
18	272,0	0,10	0,10	36,35	91,0	***	3921	3919	0,59	3921	0,0	+ 1 cycle
19				35,14	88,0	*						Tested At
20	272,8	0,10		34,28	85,8	**	3974	3973	0,30			T + 36 hrs
21	272,0	0,09	0,10	36,61	91,6	***	3913	3909	1,18	3912	0,30	+ 2 Cycles
22						*						Tested At
23	273,1	0,10		33,59		**	3941	3955	1,77			T + 36 hrs
24	270	0,09	0,10	36,35		***	3937	3935	0,59	3934	0,89	+ 2 Cycles
Mean 1-24	272,0						3935					

* TESTED HOT

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE A.II.8

SPECIMEN SERIES : CCX

TEMPERATURE : 70°C

TREATMENT : SATURATED DURING HEATING

Spec. No.	PULSE VELOCITY				DYNAMIC YOUNG'S MODULUS				POISSON'S RATIO			
	* m/sec	** and *** m/sec	R.R %		* GPa	** and *** GPa	R.R %		*	** and ***	R.R %	
1	4482				36,05				0,310			
2	4590				36,65				0,316			
3	4646				35,85				0,330			
Mean of 1,2,3	4571				36,18				0,319			
4												
5	4535	4535	98,9	**	36,13	35,44	93,7	**	0,313	0,322	103,5	**
6	4646	4732	102,6	***	36,65	36,61	96,8	***	0,327	0,337	108,4	***
7												
8	4509	4482	87,2	**	36,25	34,81	92,1	**	0,313	0,321	103,2	**
9	4704	4732	102,6	***	35,93	35,76	94,6	***	0,338	0,342	110,0	***
10												
11	4618	4563	98,9	**	36,01	34,69	91,7	**	0,329	0,332	106,8	**
12	4590	4675	101,4	***	36,82	34,88	92,3	***	0,322	0,345	110,9	***
13												
14	4509	4456	96,6	**	36,24	34,09	90,2	**	0,312	0,323	103,9	**
15	4536	4590	99,5	***	36,10	35,10	92,8	***	0,319	0,333	107,1	***
16												
17	4563	4482	97,2	**	35,58	33,03	87,4	**	0,326	0,336	108,0	**
18	4590	4618	100,1	***	36,19	35,08	92,0	***	0,323	0,335	107,7	***
19												
20	4646	4563	98,9	**	36,21	34,19	90,4	**	0,333	0,338	108,7	**
21	4563	4590	99,5	***	35,97	34,90	92,3	***	0,321	0,332	106,8	***
22												
23	4536	4405		**	36,38	33,96		**	0,315	0,317		**
24	4618	4618		***	37,23	36,78		***	0,321	0,324		***
Mean of 1-24	4583				36,26				0,322			

* TESTED BEFORE HEATING

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE A.II.8 (contd.)

SPECIMEN SERIES : CCX

TEMPERATURE : 100°C

TREATMENT : SATURATED DURING HEATING

INITIAL WATER CONTENT = 338,5 g = W_t

VIZ. W_c = 174 g = 51,4%; W_n = 90 g = 26,6%; W_g = 74,5 g = 22,0%

Spec. No.	DEFORMATION			COMPRESSIVE STRENGTH			WATER LOSS					HEAT TREATMENT
	Initial length mm	Strain ** mm/m	Strain *** mm/m	MPa	R.R %		Mass before heat A(g)	Mass after heat B(g)	$\frac{A-B}{W_t}$ %	Mass after wett. C(g)	$\frac{A-C}{W_t}$ %	
1	271,5			36,34			3890					No Heating.
2	273,3			38,67			3978					Tested at
3	273,6			39,62			3946					Room Temp.
Mean 1,2,3	272,8			38,21			3937					
4				30,66	76,7	*						Tested Imm.
5	272,8	0,06		32,82	82,2	**	3955	3954	0,3			Max. Temp.
6	273,1	0,04	0,04	34,11	85,4	***	3920	3917	0,9	3921	-0,3	Attained (Time T)
7				28,77	72,0	*						Tested At
8	269,7	0,06		34,28	85,8	**	3815	3812	0,9			T + 12 hrs
9	272,0	0,06	0,05	32,64	81,7	***	3912	3908	1,2	3912	0,0	
10				32,21	80,6	*						Tested At
11	267,5	0,09		31,87	79,8	**	3818	3812	1,8			T + 24 hrs
12	271,3	0,07	0,08	33,42	83,7	***	3882	3882	0,0	3885	-0,9	
13				34,37	86,0	*						Tested At
14	272,8	0,08		34,62	86,7	**	3967	3965	0,6			T + 36 hrs
15	272,5	0,08	0,10	34,54	86,5	***	3938	3937	0,3	3940	-0,6	
16				33,07	82,8	*						Tested At
17	272,3	0,09		34,37	86,0	**	3957	3956	0,3			T + 36 hrs
18	273,1	0,08	0,08	33,42	83,7	***	3954	3954	0,0	3957	-0,9	+ 1 cycle
19				33,85	84,7	*						Tested At
20	271,5	0,09		32,90	82,4	**	3945	3946	-0,3			T + 36 hrs
21	273,3	0,10	0,09	35,92	89,9	***	3948	3947	0,3	3949	-0,3	+ 2 Cycles
22						*						Tested At
23	271,3	0,10		34,45		**	3904	3901	0,9			T + 36 hrs
24	272,3	0,08	0,10	36,43		***	3900	3902	-0,6	3904	-1,2	+ 2 Cycles
Mean 1-24	272,0						3915					

* TESTED HOT

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE A.II.9

SPECIMEN SERIES : CCX

TEMPERATURE : 100°C

TREATMENT : SATURATED DURING HEATING

Spec. No.	PULSE VELOCITY				DYNAMIC YOUNG'S MODULUS				POISSON'S RATIO			
	* m/sec	** and *** m/sec	R.R %		* GPa	** and *** GPa	R.R %		*	** and ***	R.R %	
1	4590				35,88				0,324			
2	4590				36,93				0,320			
3	4618				36,20				0,327			
Mean of 1,2,3	4598				36,34				0,324			
4												
5	4646	4482	97,2	**	37,04	33,47	88,5	**	0,325	0,330	106,1	**
6	4618	4563	98,9	***	36,86	33,97	89,8	***	0,320	0,336	108,0	***
7												
8	4646	4456	96,6	**	35,44	30,92	81,8	**	0,330	0,330	106,1	**
9	4675	4536	98,4	***	35,92	32,82	86,8	***	0,335	0,342	110,0	***
10												
11	4675	4482	97,2	**	36,34	31,26	82,7	**	0,330	0,346	111,3	**
12	4733	4618	100,1	***	36,49	33,34	88,2	***	0,336	0,346	111,3	***
13												
14	4704	4509	97,8	**	36,29	32,52	86,0	**	0,338	0,344	110,6	**
15	4618	4536	98,4	***	36,08	33,04	87,4	***	0,328	0,342	110,0	***
16												
17	4618	4405	95,5	**	35,92	32,00	84,6	**	0,331	0,336	108,0	**
18	4590	4482	97,2	***	36,38	33,69	89,1	***	0,323	0,331	106,4	***
19												
20	4733	4536	98,4	**	37,11	32,86	86,9	**	0,335	0,344	110,6	**
21	4618	4563	98,9	***	36,55	34,18	90,4	***	0,324	0,336	108,0	***
22												
23	4563	4456		**	36,23	32,84		**	0,319	0,333		**
24	4618	4536		***	36,19	33,98		***	0,325	0,332		***
Mean of 1-24	4647				36,35				0,329			

* TESTED BEFORE HEATING

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE A.II.9 (contd.)

SPECIMEN SERIES : CCX

TEMPERATURE : 70°C

TREATMENT : DRYING DURING HEATING

INITIAL WATER CONTENT = 338,5 g = W_t

VIZ. W_c = 174 g = 51,4%
W_n = 90 g = 26,6%
W_g = 74,5 g = 22,0%

Spec. No.	DEFORMATION			COMPRESSIVE STRENGTH		WATER LOSS					HEAT TREATMENT
	Initial length mm	Strain ** mm/m	Strain *** mm/m	MPa	R.R %	Mass before heat A(g)	Mass after heat B(g)	$\frac{A-B}{W_t}$ %	Mass after wett. C(g)	$\frac{A-C}{W_t}$ %	
1	273,6			39,11		3799					No Heating.
2	272,5			37,21		3910					Tested at
3	268,4			39,45		3874					Room Temp.
Mean 1,2,3	271,5			38,59		3861					
4				33,59	84,1 *						Tested Imm.
5	271,8	-0,17		44,96	112,5 **	3862	3757	31,0			Max. Temp. Attained
6	274,1	-0,20	-0,07	38,59	96,6 ***	3915	3815	29,5	3901	4,1	(Time T)
7				37,90	94,9 *						Tested At
8	269,7	-0,17		39,28	98,3 **	3860	3736	36,6			T + 12 hrs
9	268,5	-0,18	-0,06	34,62	86,7 ***	3866	3734	39,0	3854	3,5	
10				36,52	91,4 *						Tested At
11	273,6	-0,15		42,89	107,4 **	3918	3780	40,8			T + 24 hrs
12	272,5	-0,18	-0,05	35,31	88,4 ***	3914	3781	39,3	3901	3,8	
13				37,04	92,7 *						Tested At
14	271,5	-0,20		39,28	98,3 **	3892	3752	41,4			T + 36 hrs
15	268,5	-0,14	-0,06	35,31	88,4 ***	3782	3633	44,0	3770	3,5	
16				42,03	105,2 *						Tested At
17	270,5	-0,21		37,90	94,9 **	3833	3670	48,2			T + 36 hrs
18	271,8	-0,21	0,06	36,00	90,1 ***	3860	3707	45,2	3847	3,8	+ 1 cycle
19				37,55	94,0 *						Tested At
20	272,5	-0,25		39,28	98,3 **	3873	3710	48,2			T + 36 hrs
21	272,8	-0,31	0,07	37,55	94,0 ***	3888	3743	42,8	3877	3,2	+ 2 Cycles
22					*						Tested At
23	272,8	-0,24		36,52	**	3996	3869	37,5	3981	4,4	T + 36 hrs
24	274,1	-0,21	0,07	41,86	***	3902	3762	41,4			+ 2 Cycles
Mean 1-24	272,0					3883					

* TESTED HOT

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE A.II.10

SPECIMEN SERIES : CCX

TEMPERATURE : 70°C

TREATMENT : DRYING DURING HEATING

Spec. No.	PULSE VELOCITY				DYNAMIC YOUNG'S MODULUS				POISSON'S RATIO			
	* m/sec	** and *** m/sec	R.R %		* GPa	** and *** GPa	R.R %		*	** and ***	R.R %	
1	4509				35,37				0,308			
2	4430				34,37				0,316			
3	4404				35,79				0,300			
Mean of 1,2,3	4448				35,16				0,308			
4												
5	4456	4430	96,1	**	34,54	32,07	84,6	**	0,315	0,325	104,5	**
6	4482	4456	96,6	***	35,31	33,58	88,8	***	0,313	0,324	104,2	***
7												
8	4404	4210	91,3	**	33,48	31,46	83,2	**	0,320	0,299	96,1	**
9	4509	4482	97,2	***	33,44	30,71	81,2	***	0,353	0,352	113,2	***
10												
11	4509	4354	94,4	**	35,68	31,60	83,6	**	0,314	0,319	102,6	**
12	4456	4404	95,5	***	34,40	32,90	87,0	***	0,319	0,325	104,5	***
13												
14	4582	4187	90,8	**	34,58	31,05	82,1	**	0,333	0,299	96,1	**
15	4430	4354	94,4	***	32,22	30,57	80,9	***	0,330	0,333	107,1	***
16												
17	4430	4187	90,8	**	33,78	28,62	75,7	**	0,291	0,320	102,9	**
18	4482	4430	96,1	***	34,53	31,58	83,5	***	0,318	0,336	108,0	***
19												
20	4354	4164	90,3	**	34,04	29,95	79,2	**	0,304	0,303	97,4	**
21	4536	4563	98,9	***	35,11	32,63	86,3	***	0,322	0,344	110,6	***
22												
23	4563	4404		**	35,98	33,70		**	0,326	0,345		**
24	4456			***	34,84			***	0,313			***
Mean of 1-24	4430				34,54				0,318			

* TESTED BEFORE HEATING

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE A.II.10 (contd.)

SPECIMEN SERIES : CCX

TEMPERATURE : 100°C

TREATMENT : DRYING DURING HEATING

INITIAL WATER CONTENT = 338,5 g = W_t

VIZ. W_c = 174 g = 51,4%; W_n = 90 g = 26,6%; W_g = 74,5 g = 22,0%

Spec. No.	DEFORMATION			COMPRESSIVE STRENGTH			WATER LOSS					HEAT TREATMENT
	Initial length mm	Strain ** mm/m	Strain *** mm/m	MPa	R.R %		Mass before heat A(g)	Mass after heat B(g)	$\frac{A-B}{W_t}$ %	Mass after wett. C(g)	$\frac{A-C}{W_t}$ %	
1	272,3			40,31			3879					No Heating.
2	270,8			40,31			3958					Tested at
3	271,1			40,31			3944					Room Temp.
Mean 1,2,3	271,4			40,31			3927					
4				31,78	79,5	*						Tested Imm. Max. Temp. Attained (Time T)
5	272,5	-0,13		36,59	91,4	**	3931	3819	33,1			
6	271,3	-0,15	-0,01	37,12	92,9	***	3912	3810	30,1	3903	2,7	
7				35,23	88,2	*						Tested At T + 12 hrs
8	272,5	-0,21		38,24	95,7	**	3869	3699	50,2			
9	271,0	-0,23	-0,07	33,16	83,0	***	3942	3764	52,6	3932	3,0	
10				36,86	92,3	*						Tested At T + 24 hrs
11	272,5	-0,25		36,35	91,0	**	3945	3747	58,5			
12	272,3	-0,23	-0,07	31,61	79,1	***	3908	3729	52,9	3893	4,4	
13				37,47	93,8	*						Tested At T + 36 hrs
14	270,8	-0,20		41,34	103,5	**	3882	3668	63,2			
15	272,8	-0,27	-0,10	37,18	78,0	***	3894	3694	59,1	3882	3,5	
16				39,36	98,5	*						Tested At T + 36 hrs + 1 cycle
17	271,0	-0,30		40,05	100,3	**	3874	3648	66,8			
18	273,3	-0,31	-0,11	28,94	72,4	***	3877	3661	63,8	3863	4,1	
19				38,07	95,3	*						Tested At T + 36 hrs + 2 Cycles
20	272,5	-0,28		39,36	98,5	**	3895	3685	62,0			
21	272,3	-0,28	-0,09	29,28	73,3	***	3946	3755	56,4	3933	3,8	
22						*						Tested At T + 36 hrs + 2 Cycles
23	271,0	-0,33		38,41		**	3853	3621	68,5			
24	272,5	-0,28	-0,08	29,28		***	3956	3744	62,6	3941	4,4	
Mean 1-24	272,0						3906					

* TESTED HOT

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE A.II.11

SPECIMEN SERIES : CCX

TEMPERATURE : 100°C

TREATMENT : DRYING DURING HEATING

Spec. No.	PULSE VELOCITY				DYNAMIC YOUNG'S MODULUS				POISSON'S RATIO			
	* m/sec	** and *** m/sec	R.R %		* GPa	** and *** GPa	R.R %		*	** and ***	R.R %	
1	4646				41,03				0,284			
2	4563				39,94				0,291			
3	4646				39,60				0,305			
Mean of 1,2,3	4618				40,19				0,293			
4												
5	4618	4305	93,3	**	40,00	32,25	85,3	**	0,294	0,310	99,7	**
6	4675	4509	97,8	***	41,59	39,32	104,0	***	0,288	0,281	90,4	***
7												
8	4590	4257	92,3	**	4121	32,61	86,2	**	0,270	0,287	92,3	**
9	4646	4330	93,9	***	41,75	35,86	94,8	***	0,285	0,289	92,9	***
10												
11	4590	4141	89,8	**	40,86	31,12	85,0	**	0,282	0,275	88,4	**
12	4675	4482	97,2	***	41,41	35,90	94,9	***	0,288	0,308	99,0	***
13												
14	4563	4164	90,3	**	40,32	32,03	84,7	**	0,279	0,275	88,4	**
15	4704	4430	96,1	***	40,53	34,65	91,6	***	0,299	0,310	99,7	***
16												
17	4590	4141	89,8	**	40,27	31,79	84,1	**	0,283	0,270	86,8	**
18	4618	4354	94,4	***	41,08	32,96	87,2	***	0,277	0,313	100,6	***
19												
20	4618	4164	90,3	**	40,07	30,98	81,9	**	0,299	0,288	92,6	**
21	4646	4330	93,9	***	41,49	35,45	93,8	***	0,286	0,292	93,7	***
22												
23	4646	4119		**	39,52	30,46		**	0,298	0,281		**
24	4590	4257		***	41,80	34,84		***	0,274	0,285		***
Mean of 1-24	4616				40,85				0,286			

* TESTED BEFORE HEATING

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE A.II.11 (contd.)

SPECIMEN SERIES : CCX

TEMPERATURE : 150°C

TREATMENT : DRYING DURING HEATING

INITIAL WATER CONTENT = 338,5 g = W_t

VIZ. W_c = 174 g = 51,4%; W_n = 90 g = 26,6%; W_g = 74,5 g = 22,0%

Spec. No.	DEFORMATION			COMPRESSIVE STRENGTH			WATER LOSS					HEAT TREATMENT
	Initial length mm	Strain ** mm/m	Strain *** mm/m	MPa	R.R %		Mass before heat A(g)	Mass after heat B(g)	$\frac{A-B}{W_t}$ %	Mass after wett. C(g)	$\frac{A-C}{W_t}$ %	
1	272,5			37,47			3963					No Heating, Tested at Room Temp.
2	272,8			37,04			3949					
3	270,4			41,69			3986					
Mean 1,2,3	271,9			38,73			3946					
4				41,34	103,5	*						Tested Imm. Max. Temp. Attained (Time T)
5	272,3	-0,22		38,76	97,0	**	3897	3689	61,4			
6	272,3	-0,20	-0,03	31,01	77,6	***	3910	3696	63,2	3893	5,0	
7				39,62	99,2	*						Tested At T + 12 hrs
8	272,5	-0,26		42,89	107,4	**	3929	3705	66,2			
9	274,1	-0,26	-0,06	27,91	69,9	***	3901	3677	66,2	3885	5,6	
10				46,60	116,6	*						Tested At T + 24 hrs
11	272,5	-0,29		40,83	102,2	**	3863	3641	65,6			
12	270,3	-0,26	-0,06	32,30	80,9	***	3882	3658	66,2	3864	5,3	
13				39,79	99,6	*						Tested At T + 36 hrs
14	273,6	-0,30		41,17	103,1	**	3923	3689	69,1			
15	274,3	-0,30	-0,05	30,32	75,9	***	3943	3718	66,5	3927	4,7	
16				43,75	109,5	*						Tested At T + 36 hrs + 1 cycle
17	272,5	-0,28		42,72	106,9	**	3921	3688	68,8			
18	272,8	-0,32	-0,01	31,01	77,6	***	3932	3696	69,7	3913	5,6	
19				42,72	106,9	*						Tested At T + 36 hrs + 2 Cycles
20	272,3	-0,33		40,14	100,5	**	3933	3704	67,7			
21	272,8	-0,34	-0,02	31,35	78,5	***	3909	3672	70,0	3890	5,6	
22						*						Tested At T + 36 hrs + 2 Cycles
23	272,5	-0,35		41,43		**	3906	3668	70,3			
24	270,5	-0,31	-0,03	31,87		***	3903	3662	71,2	3885	5,3	
Mean 1-24	272,5						3911					

* TESTED HOT

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE A.II.12

SPECIMEN SERIES : CCX

TEMPERATURE : 150°C

TREATMENT : DRYING DURING HEATING

Spec. No.	PULSE VELOCITY				DYNAMIC YOUNG'S MODULUS				POISSON'S RATIO			
	* m/sec	** and *** m/sec	R.R %		* GPa	** and *** GPa	R.R %		*	** and ***	R.R %	
1	4646				40,13				0,295			
2	4618				41,32				0,288			
3	4590				41,07				0,288			
Mean of 1,2,3	4618				40,84				0,289			
4												
5	4646	4141	89,8	**	40,16	29,84	78,9	**	0,294	0,299	96,1	**
6	4590	4281	92,8	***	40,82	34,43	91,1	***	0,279	0,290	93,2	***
7												
8	4618	4119	89,3	**	40,72	29,61	78,3	**	0,287	0,299	96,1	**
9	4536	4233	91,8	***	40,03	34,34	90,8	***	0,274	0,278	89,4	***
10												
11	4563	4053	87,9	**	39,42	28,02	74,1	**	0,284	0,301	96,8	**
12	4646	4305	93,3	***	39,90	33,68	89,1	***	0,298	0,302	97,1	***
13												
14	4563	3990	86,5	**	39,85	29,76	78,7	**	0,284	0,309	99,4	**
15	4563	4305	93,3	***	41,14	33,85	89,5	***	0,271	0,301	96,8	***
16												
17	4618	4032	87,4	**	39,36	27,32	72,3	**	0,299	0,310	99,7	**
18	4646	4305	93,3	***	40,46	33,77	89,3	***	0,294	0,302	97,1	***
19												
20	4618	4075	88,4	**	40,86	28,12	74,4	**	0,286	0,309	99,4	**
21	4590	4305	93,3	***	40,23	33,80	89,4	***	0,284	0,300	96,5	***
22												
23	4536	3888		**	40,16	29,91		**	0,275	0,236		**
24	4563	4281		***	40,28	33,25		***	0,282	0,304		***
Mean of 1-24	4595				40,24				0,285			

* TESTED BEFORE HEATING

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE A.II.12 (contd.)

SPECIMEN SERIES : CCX

TEMPERATURE : 250°C

TREATMENT : DRYING DURING HEATING

INITIAL WATER CONTENT = 338,5 g = W_t

VIZ. W_c = 174 g = 51,4%

W_n = 90 g = 26,6%

W_g = 75,5 g = 22,0%

Spec. No.	DEFORMATION			COMPRESSIVE STRENGTH			WATER LOSS					HEAT TREATMENT
	Initial length mm	Strain ** mm/m	Strain *** mm/m	MPa	R.R %		Mass before heat A(g)	Mass after heat B(g)	$\frac{A-B}{W_t}$ %	Mass after wett. C(g)	$\frac{A-C}{W_t}$ %	
1	270,3			40,91			3946					No Heating.
2	272,4			39,36			3883					Tested at
3	273,0			40,31			3869					Room Temp.
Mean 1,2,3	271,9			40,19			3899					
4				41,00	102,6	*						Tested Imm.
5	271,8	-0,17		37,55	94,0	**						Max. Temp.
6	271,3	-0,21	0,44	29,97	75,0	***	3884	3635	73,9	3874	3,0	Attained (Time T)
7				42,03	105,2	*						Tested At
8	272,3	-0,22		39,19	98,1	**	3869	3633	69,7			T + 12 hrs
9	271,0	-0,17	0,52	29,46	73,7	***	3837	3593	72,1	3829	2,4	
10				42,89	107,4	*						Tested At
11	271,5	-0,21		40,48	101,3	**	3915	3663	74,4			T + 24 hrs
12	270,5	-0,22	0,22	31,78	79,5	***	3879	3658	65,3	3868	3,2	
13				41,69	104,4	*						Tested At
14	271,5	-0,19		38,76	97,0	**	3898	3635	77,7			T + 36 hrs
15	272,0	-0,24	0,26	30,49	73,6	***	3862	3621	71,2	3848	4,1	
16				44,96	112,5	*						Tested At
17	272,8	-0,18		38,07	95,3	**	3888	3616	80,4			T + 36 hrs
18	272,0	-0,22	0,36	32,30	80,9	***	3910	3669	71,2	3901	2,7	+ 1 cycle
19				44,62	111,7	*						Tested At
20	271,0	-0,22		39,45	98,7	**	3946	3728	64,4			T + 36 hrs
21	271,5	-0,29	0,22	30,92	77,4	***	3883	3634	73,6	3871	3,5	+ 2 Cycles
22						*						Tested At
23	271,3	-0,29		39,45		**	3777	3514	77,7			T + 36 hrs
24	273,3	-0,25	0,24	31,01		***	3957	3719	70,3	3946	3,2	+ 2 Cycles
Mean 1-24												

* TESTED HOT

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE A.II.13

SPECIMEN SERIES : CCX

TEMPERATURE : 250°C

TREATMENT : DRYING DURING HEATING

Spec. No.	PULSE VELOCITY				DYNAMIC YOUNG'S MODULUS				POISSON'S RATIO			
	* m/sec	** and *** m/sec	R.R %		* GPa	** and *** GPa	R.R %		*	** and ***	R.R %	
1	4762				37,91				0,334			
2	4675				39,43				0,304			
3	4703				37,83				0,321			
Mean of 1,2,3	4713				38,39				0,320			
4												
5	4703	3810	82,6	**	39,05	23,26	61,5	**	0,315	0,326	104,8	**
6	4563	4305	93,3	***	37,75	31,22	82,6	***	0,304	0,326	104,8	***
7												
8	4675	3791	82,2	**	38,27	22,50	59,5	**	0,313	0,327	105,1	**
9	4563	4305	93,3	***	36,75	30,83	81,5	***	0,309	0,326	104,8	***
10												
11	4675	3754	81,4	**	37,56	22,47	59,4	**	0,323	0,325	104,5	**
12	4646	4456	96,6	***	39,50	33,74	89,2	***	0,301	0,324	104,2	***
13												
14	4703	3735	81,0	**	37,50	20,47	51,4	**	0,329	0,345	110,9	**
15	4675	4456	96,6	***	36,61	33,12	87,6	***	0,326	0,326	104,8	***
16												
17	4618	3432	74,4	**	37,06	19,13	50,6	**	0,316	0,314	101,0	**
18	4703	4430	96,1	***	39,50	32,73	86,6	***	0,310	0,330	106,1	***
19												
20	4732	3908	84,7	**	40,67	23,51	62,2	**	0,309	0,340	109,3	**
21	4675	4430	96,1	***	37,90	31,83	84,2	***	0,318	0,336	108,0	***
22												
23	4646	3699		**	36,36	18,88		**	0,318	0,352		**
24	4618	4405		***	37,95	34,12		***	0,314	0,316		***
Mean of 1-24	4657				38,03				0,315			

* TESTED BEFORE HEATING

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE A.II.13 (contd.)

SPECIMEN SERIES : CCX

TEMPERATURE : 400°C

TREATMENT : DRYING DURING HEATING

INITIAL WATER CONTENT = 338,5 g = W_t

VIZ. W_c = 174 g = 51,4%; W_n = 90 g = 26,6%; W_g = 74,5 g = 22,0%

Spec. No.	DEFORMATION			COMPRESSIVE STRENGTH			WATER LOSS					HEAT TREATMENT
	Initial length mm	Strain ** mm/m	Strain *** mm/m	MPa	R.R %		Mass before heat A(g)	Mass after heat B(g)	$\frac{A-B}{W_t}$ %	Mass after wett. C(g)	$\frac{A-C}{W_t}$ %	
1	270,3			38,76			3858					No Heating. Tested at Room Temp.
2	271,2			38,42			3929					
3	274,2			34,97			3794					
Mean 1,2,3	271,9			37,38			3860					
4				34,8	85,1	*						Tested Imm. Max. Temp. Attained (Time T)
5	271,5	0,90		30,15	75,5	**	3204	3631	80,6			
6	270,3	0,68	1,46	27,73	69,4	***	3884	3600	83,9	3874	3,0	
7				36,69	91,8	*						Tested At T + 12 hrs
8	271,8	0,63		30,83	77,2	**	3905	3633	80,4			
9	273,1	1,10	3,14	27,73	69,4	***	3923	3637	84,5	3920	0,9	
10				34,45	86,2	*						Tested At T + 24 hrs
11	272,8	1,34		30,49	76,3	**	3915	3625	85,7			
12	269,7	0,69	1,48	28,42	71,1	***	3855	3579	81,5	3548	2,1	
13				35,66	89,3	*						Tested At T + 36 hrs
14	268,5	1,74		30,83	77,2	**	3865	3568	87,7			
15	269,5	1,21	2,30	29,46	73,7	***	3883	3609	80,9	3881	0,6	
16				35,66	89,3	*						Tested At T + 36 hrs + 1 cycle
17	271,5	1,04		32,38	81,1	**	3886	3611	81,2			
18	268,5	1,08	2,53	27,22	68,1	***	3825	3547	82,1	3825	0,0	
19				35,14	88,0	*						Tested At T + 36 hrs + 2 Cycles
20	270,8	0,69		32,21	80,6	**	3794	3496	88,0			
21	272,5	0,51	1,22	31,87	79,8	***	3929	3666	77,7	3921	2,4	
22						*						Tested At T + 36 hrs + 2 Cycles
23	270,5	1,07		30,66		**	3780	3492	85,1			
24	271,3	0,73	1,46	31,18		***	3896	3638	76,2	3891	1,5	
Mean 1-24	271,0						3873					

* TESTED HOT

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE A.II.14

SPECIMEN SERIES : CCX

TEMPERATURE : 400°C

TREATMENT : DRYING DURING HEATING

Spec. No.	PULSE VELOCITY				DYNAMIC YOUNG'S MODULUS				POISSON'S RATIO			
	* m/sec	** and *** m/sec	R.R %		* GPa	** and *** GPa	R.R %		*	** and ***	R.R %	
1	4704				38,01				0,320			
2	4763				37,75				0,332			
3	4733				37,91				0,315			
Mean of 1,2,3	4733				37,89				0,322			
4												
5	4763	2812	61,0	**	37,22	6,68	17,7	**	0,266	0,426	137,0	**
6	4675	4281	92,8	***	36,37	26,24	69,4	***	0,331	0,365	117,4	***
7												
8	4763	3073	66,6	**	37,50	7,76	20,5	**	0,333	0,429	137,9	**
9	4763	4330	93,9	***	37,75	24,77	65,5	***	0,331	0,380	122,2	***
10												
11	4763	2683	58,2	**	38,53	6,71	17,7	**	0,325	0,424	136,3	**
12	4733	4330	93,9	***	38,72	24,15	63,9	***	0,319	0,369	118,6	***
13												
14	4763	2540	55,1	**	38,53	4,66	12,3	**	0,326	0,438	140,8	**
15	4763	4379	94,9	***	39,32	25,04	66,2	***	0,320	0,382	122,8	***
16												
17	4675	2442	52,9	**	38,76	5,96	15,8	**	0,311	0,408	131,2	**
18	4763	4257	92,3	***	37,84	21,26	56,2	***	0,328	0,397	127,7	***
19												
20	4704	2466	53,5	**	37,06	6,68	17,7	**	0,322	0,392	126,0	**
21	4823	4430	96,1	***	39,46	23,35	61,8	***	0,327	0,396	127,3	***
22												
23	4675	2474		**	39,90	5,31		**	0,292	0,420		**
24	4792	4456		***	38,29	23,00		***	0,330	0,399		***
Mean of 1-24	4749				38,16				0,319			

* TESTED BEFORE HEATING

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE A.II.14 (contd.)

SPECIMEN SERIES : CCY

TEMPERATURE : 70°C

TREATMENT : SATURATED DURING HEATING

INITIAL WATER CONTENT = 301 g = W_t

VIZ. W_c = 155 g = 51,5%
W_n = 80 g = 26,6%
W_g = 66 g = 21,9%

Spec. No.	DEFORMATION			COMPRESSIVE STRENGTH			WATER LOSS					HEAT TREATMENT
	Initial length mm	Strain ** mm/m	Strain *** mm/m	MPa	R.R %		Mass before heat A(g)	Mass after heat B(g)	$\frac{A-B}{W_t}$ %	Mass after wett. C(g)	$\frac{A-C}{W_t}$ %	
1	272,5			42,20			3974					No Heating.
2	272,0			40,91			3901					Tested at
3	273,7			42,98			3980					Room Temp.
Mean 1,2,3	272,7			42,03			3952					
4				35,23	85,7	*						Tested Imm.
5	273,1	0,08		41,26	100,3	**	3936	3937	-0,3			Max. Temp.
6	272,8	0,06	0,04	44,10	107,2	***	3936	3938	-0,7	3941	-1,7	Attained (Time T)
7				36,26	88,2	*						Tested At
8	273,1	0,07		36,95	89,9	**	3924	3924	0,0			T + 12 hrs
9	273,1	0,09	0,09	38,59	93,8	***	3933	3933	0,0	3935	-0,3	
10				34,97	85,0	*						Tested At
11	271,0	0,10		36,61	89,0	**	3886	3886	0,0			T + 24 hrs
12	270,3	0,09	0,08	37,38	90,9	***	3920	3920	0,0	3921	-0,3	
13				36,52	88,8	*						Tested At
14	272,3	0,10		37,81	92,0	**	3949	3948	0,3			T + 36 hrs
15	272,5	0,08	0,08	37,90	92,2	***	3923	3923	0,0	3925	-0,7	
16				37,29	90,7	*						Tested At
17	274,8	0,08		37,04	90,1	**	3941	3939	0,7			T + 36 hrs
18	272,0	0,11	0,12		94,3	***	3885	3886	-0,3	3887	-0,7	+ 1 cycle
19				35,77	87,0	*						Tested At
20	270,8	0,08		37,72	91,7	**	3885	3883	0,7			T + 36 hrs
21	270,0	0,10	0,09	39,13	95,2	***	3876	3875	0,3	3878	-0,7	+ 2 Cycles
22						*						Tested At
23	271,0	0,08		37,72		**	3899	3929	2,3			T + 36 hrs
24	270,8	0,09	0,09	39,68		***	3941	3940	0,3	3943	-0,7	+ 2 Cycles
Mean 1-24	272,0						3916					

* TESTED HOT

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE A.II.15

SPECIMEN SERIES : CCY

TEMPERATURE : 70°C

TREATMENT : SATURATED DURING HEATING

Spec. No.	PULSE VELOCITY				DYNAMIC YOUNG'S MODULUS				POISSON'S RATIO			
	* m/sec	** and *** m/sec	R.R %		* GPa	** and *** GPa	R.R %		*	** and ***	R.R %	
1	4675				37,53				0,326			
2	4646				37,01				0,322			
3	4704				38,10				0,325			
Mean of 1,2,3	4675				37,55				0,324			
4												
5	4733	4704	100,5	**	37,76	36,88	94,3	**	0,328	0,331	107,1	**
6	4618	4590	98,0	***	38,24	38,15	97,6	***	0,328	0,307	99,4	***
7												
8	4618	4590	98,0	**	39,33	35,26	90,2	**	0,300	0,329	106,5	**
9	4618	4509	96,3	***	37,10	36,27	92,8	***	0,319	0,311	100,6	***
10												
11	4646	4563	97,5	**	36,85	35,06	89,7	**	0,323	0,327	105,8	**
12	4590	4563	97,5	***	37,99	37,24	95,2	***	0,310	0,312	101,0	***
13												
14	4618	4590	98,0	**	37,88	36,05	92,2	**	0,315	0,326	105,5	**
15	4704	4618	98,6	***	37,78	36,34	92,9	***	0,324	0,325	105,2	***
16												
17	4675	4590	98,0	**	37,30	35,19	90,0	**	0,323	0,329	106,5	**
18	4590	4618	98,6	***	36,12	35,46	90,7	***	0,321	0,330	106,8	***
19												
20	4733	4648	99,3	**	36,81	34,53	88,3	**	0,334	0,329	106,5	**
21	4733	4733	101,1	***	36,77	36,11	92,4	***	0,334	0,330	106,8	***
22												
23	4646	4590		**	38,50	36,17		**	0,312	0,325		**
24	4646	4636		***	37,10	36,36		***	0,322	0,321		***
Mean of 1-24	4655				37,54				0,320			

* TESTED BEFORE HEATING

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE A.II.15 (contd.)

SPECIMEN SERIES : CCY

TEMPERATURE : 100°C

TREATMENT : SATURATED DURING HEATING

INITIAL WATER CONTENT = 301 g = W_t

VIZ. W_c = 155 g = 51,5%

W_n = 80 g = 26,6%

W_g = 66 g = 21,9%

Spec. No.	DEFORMATION			COMPRESSIVE STRENGTH			WATER LOSS					HEAT TREATMENT
	Initial length mm	Strain ** mm/m	Strain *** mm/m	MPa	R.R %		Mass before heat A(g)	Mass after heat B(g)	$\frac{A-B}{W_t}$ %	Mass after wett. C(g)	$\frac{A-C}{W_t}$ %	
1	270,5			42,20			3904					No Heating.
2	274,6			38,33			3907					Tested at
3	270,5			41,86			3911					Room Temp.
Mean 1,2,3	271,9			40,80			3907					
4				32,30	78,6	*						Tested Imm.
5	271,0	0,06		32,99	80,2	**	3833	3830	1,0			Max. Temp.
6	272,8	0,06	0,07	39,10	95,1	***	3987	3984	1,0	3983	1,3	Attained (Time T)
7				30,06	73,1	*						Tested At
8	271,8	0,10		30,58	74,4	**	3831	3827	1,3			T + 12 hrs
9	273,3	0,09	0,09	33,25	80,9	***	3974	3970	1,3	3970	1,3	
10				31,78	77,3	*						Tested At
11	272,3	0,09		33,16	80,6	**	3936	3933	1,0			T + 24 hrs
12	272,3	0,10	0,10	34,02	82,7	***	3970	3966	1,3	3967	1,0	
13				34,54	84,0	*						Tested At
14	272,8	0,11		35,31	85,9	**	3869	3867	0,7			T + 36 hrs
15	272,8	0,11	0,11	36,69	89,2	***	3989	3885	1,3	3886	1,0	
16				33,68	81,9	*						Tested At
17	273,3	0,09		36,09	87,8	**	3922	3923	-0,3			T + 36 hrs
18	272,5	0,13	0,14	34,28	83,4	***	3941	3942	-0,3	3941	0,0	+ 1 cycle
19				36,86	89,6	*						Tested At
20	272,5	0,10		37,55	91,3	**	3968	3966	0,7			T + 36 hrs
21	272,0	0,09	0,08	39,45	95,9	***	3941	3938	1,0	3939	0,7	+ 2 Cycles
22						*						Tested At
23	273,1	0,10		36,17		**	3968	3963	1,7			T + 36 hrs
24	272,0	0,09	0,10	37,55		***	3888	3890	-0,7	3889	-0,3	+ 2 Cycles
Mean 1-24	272,5						3930					

* TESTED HOT

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE A.II.16

SPECIMEN SERIES : CCY

TEMPERATURE : 100°C

TREATMENT : SATURATED DURING HEATING

Spec. No.	PULSE VELOCITY				DYNAMIC YOUNG'S MODULUS				POISSON'S RATIO			
	* m/sec	** and *** m/sec	R.R %		* GPa	** and *** GPa	R.R %		*	** and ***	R.R %	
1	4675				38,93				0,312			
2	4590				35,76				0,323			
3	4675				38,07				0,320			
Mean of 1,2,3	4646				37,59				0,318			
4												
5	4704	4590	98,0	**	36,73	34,14	87,3	**	0,327	0,337	109,1	**
6	4792	4646	99,2	***	38,97	35,97	92,0	***	0,330	0,335	108,4	***
7												
8	4675	4509	96,3	**	35,85	31,68	81,0	**	0,330	0,342	110,7	**
9	4646	4618	98,6	***	38,14	34,66	88,6	***	0,317	0,340	110,0	***
10												
11	4675	4536	96,9	**	37,89	33,89	86,7	**	0,321	0,335	108,4	**
12	4675	4590	98,0	***	37,45	34,41	88,0	***	0,327	0,340	110,0	***
13												
14	4675	4509	96,3	**	36,34	32,95	84,3	**	0,328	0,334	108,1	**
15	4618	4536	96,9	***	37,97	32,90	84,1	***	0,316	0,339	109,7	***
16												
17	4646	4590	98,0	**	38,16	34,25	87,6	**	0,313	0,303	98,1	**
18	4536	4563	97,5	***	36,98	33,33	85,2	***	0,310	0,342	110,7	***
19												
20	4675	4509	96,3	**	39,06	34,63	88,6	**	0,314	0,328	106,1	**
21	4733	4646	99,2	***	38,31	35,72	91,4	***	0,326	0,335	108,4	***
22												
23	4646	4563		**	37,54	34,47		**	0,322	0,335		**
24	4563	4536		***	37,03	34,24		***	0,310	0,330		***
Mean of 1-24	4700				37,60				0,321			

* TESTED BEFORE HEATING

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE A.II.16 (contd.)

SPECIMEN SERIES : CCY

TEMPERATURE : 70°C

TREATMENT : DRYING DURING HEATING

INITIAL WATER CONTENT = 301 g = W_t

VIZ. W_c = 155 g = 51,5%

W_n = 80 g = 26,6%

W_g = 66 g = 21,9%

Spec. No.	DEFORMATION			COMPRESSIVE STRENGTH			WATER LOSS					HEAT TREATMENT
	Initial length mm	Strain ** mm/m	Strain *** mm/m	MPa	R.R %		Mass before heat A(g)	Mass after heat B(g)	$\frac{A-B}{W_t}$ %	Mass after wett. C(g)	$\frac{A-C}{W_t}$ %	
1	270,2			44,01			3916					No Heating.
2	270,8			44,61			3942					Tested at
3	273,2			41,77			3951					Room Temp.
Mean 1,2,3	271,4			43,46			3936					
4				39,53	96,1	*						Tested Imm.
5	272,0	-0,13		43,67	106,2	**	3860	3792	22,6			Max. Temp. Attained
6	271,0	-0,13	+0,02	39,88	97,0	***	3915	3851	21,3	3901	4,3	(Time T)
7				41,69	101,4	*						Tested At
8	272,3	-0,14		42,12	102,4	**	3913	3820	35,5			T + 12 hrs
9	271,5	-0,11	+0,01	37,72	91,7	***	3951	3864	37,5	3945	2,0	
10				40,83	99,3	*						Tested At
11	270,8	-0,15		42,12	102,4	**	3947	3852	34,9			T + 24 hrs
12	270,8	-0,14	-0,02	39,36	95,7	***	3939	3846	30,9	3930	3,0	
13				40,74	99,1	*						Tested At
14	273,3	-0,19		39,10	95,1	**	3949	3837	37,2			T + 36 hrs
15	274,3	-0,15	-0,02	39,89	97,0	***	3983	3880	34,2	3974	3,0	
16				42,29	102,8	*						Tested At
17	272,3	-0,17		42,29	102,8	**	3945	3828	38,9			T + 36 hrs
18	270,8	-0,20	-0,03	39,71	96,6	***	3891	3772	39,5	3883	2,7	+ 1 cycle
19				44,79	108,9	*						Tested At
20	272,8	-0,20		42,72	103,9	**	3946	3828	39,2			T + 36 hrs
21	270,3	-0,18	-0,02	39,45	95,9	***	3940	3838	33,9	3934	2,0	+ 2 Cycles
22						*						Tested At
23	272,0	-0,20		39,96		**	3942	3827	41,5			T + 36 hrs
24	272,0	-0,21	-0,03	37,98		***	3977	3865	37,2	3969	2,7	+ 2 Cycles
Mean 1-24	271,8						3936					

* TESTED HOT

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE A.II.17

SPECIMEN SERIES : CCY

TEMPERATURE : 70°C

TREATMENT : DRYING DURING HEATING

Spec. No.	PULSE VELOCITY				DYNAMIC YOUNG'S MODULUS				POISSON'S RATIO			
	* m/sec	** and *** m/sec	R.R %		* GPa	** and *** GPa	R.R %		*	** and ***	R.R %	
1	4675				40,42				0,301			
2	4646				42,03				0,283			
3	4704				40,89				0,300			
Mean of 1,2,3	4675				41,11				0,295			
4												
5	4590	4509	96,3	**	40,28	39,84	101,9	**	0,280	0,261	84,5	**
6	4618	4618	98,6	***	42,58	43,19	110,5	***	0,289	0,260	84,1	***
7												
8	4704	4590	98,0	**	40,49	38,94	99,6	**	0,302	0,289	93,5	**
9	4646	4646	99,2	***	41,43	42,00	107,4	***	0,289	0,282	91,3	***
10												
11	4733	4536	96,9	**	40,99	39,93	102,1	**	0,307	0,197	63,8	**
12	4675	4675	99,9	***	40,91	40,82	104,4	***	0,298	0,298	96,4	***
13												
14	4675	4536	96,9	**	42,00	39,56	101,2	**	0,285	0,273	88,3	**
15	4704	4704	100,5	***	42,19	41,93	107,2	***	0,290	0,292	94,5	***
16												
17	4704	4509	96,3	**	43,22	39,02	99,8	**	0,280	0,274	88,7	**
18	4590	4618	98,6	***	42,72	41,69	106,6	***	0,259	0,275	89,0	***
19												
20	4618	4482	95,7	**	41,57	38,00	97,2	**	0,280	0,280	90,6	**
21	4763	4733	101,1	***	42,39	42,94	109,8	***	0,299	0,289	93,5	***
22												
23	4675	4536		**	41,73	38,14		**	0,289	0,288		**
24	4675	4646		***	41,61	41,34		***	0,294	0,291		***
Mean of 1-24	4675				41,64				0,287			

* TESTED BEFORE HEATING

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE A.II.17 (contd.)

SPECIMEN SERIES : CCY

TEMPERATURE : 100°C

TREATMENT : DRYING DURING HEATING

INITIAL WATER CONTENT = 301 g = W_t

VIZ. W_c = 155 g = 51,5%

W_n = 80 g = 26,6%

W_g = 66 g = 21,9%

Spec. No.	DEFORMATION			COMPRESSIVE STRENGTH			WATER LOSS					HEAT TREATMENT
	Initial length mm	Strain ** mm/m	Strain *** mm/m	MPa	R.R %		Mass before heat A(g)	Mass after heat B(g)	$\frac{A-B}{W_t}$ %	Mass after wett. C(g)	$\frac{A-C}{W_t}$ %	
1	271,4			38,41			3904					No Heating.
2	272,9			35,66			3927					Tested at
3	270,3			38,93			3886					Room Temp.
Mean 1,2,3	271,5			37,67			3906					
4				31,18	75,8	*						Tested Imm.
5	269,5	-0,13		36,17	88,0	**	3888	3766	40,5			Max. Temp.
6	273,6	-0,14	-0,01	33,94	82,5	***	3919	3803	38,5	3905	4,7	Attained (Time T)
7				34,11	83,0	*						Tested At
8	271,3	-0,21		37,38	90,(	**	3833	3666	55,5			T + 12 hrs
9	272,0	-0,20	-0,05	31,35	76,2	***	3876	3697	59,5	3861	5,0	
10				34,62	84,2	*						Tested At
11	271,3	-0,22		36,69	89,2	**	3829	3648	60,1			T + 24 hrs
12	270,0	-0,18	-0,04	31,35	76,2	***	3839	3657	60,5	3823	5,3	
13				38,41	93,4	*						Tested At
14	270,3	-0,22		38,76	94,3	**	3852	3661	63,5			T + 36 hrs
15	270,0	-0,22	-0,08	32,21	78,3	***	3898	3721	58,8	3883	5,0	
16				38,07	92,6	*						Tested At
17	268,5	-0,26		37,38	90,9	**	3812	3613	66,1			T + 36 hrs
18	271,0	-0,22	-0,06	32,90	80,0	***	3865	3673	63,8	3848	5,6	+ 1 cycle
19				39,45	95,9	*						Tested At
20	273,1	-0,25		38,59	93,8	**	3853	3653	66,4			T + 36 hrs
21	270,0	-0,24	-0,08	28,25	68,7	***	3869	3678	63,5	3852	5,6	+ 2 Cycles
22						*						Tested At
23	270,0	-0,28		38,41		**	3879	3674	68,1			T + 36 hrs
24	271,3	-0,25	-0,09	32,56		***	3841	3631	69,8	3819	7,3	+ 2 Cycles
Mean 1-24	270,8						3862					

* TESTED HOT

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE A.II.18

SPECIMEN SERIES : CCY

TEMPERATURE : 100°C

TREATMENT : DRYING DURING HEATING

Spec. No.	PULSE VELOCITY				DYNAMIC YOUNG'S MODULUS				POISSON'S RATIO			
	* m/sec	** and *** m/sec	R.R %		* GPa	** and *** GPa	R.R %		*	** and ***	R.R %	
1	4762				39,17				0,321			
2	4732				38,91				0,319			
3	4732				39,72				0,312			
Mean of 1,2,3	4742				39,27				0,317			
4												
5	4704	4354	93,0	**	40,08	30,55	78,1	**	0,307	0,332	107,4	**
6	4762	4618	98,6	***	40,79	35,82	91,6	***	0,306	0,327	105,8	***
7												
8	4704	4330	92,5	**	39,82	28,16	72,0	**	0,302	0,342	110,7	**
9	4675	4590	98,0	***	40,34	32,21	82,4	***	0,300	0,350	113,3	***
10												
11	4762	4254	90,9	**	39,26	27,85	71,2	**	0,314	0,335	108,1	**
12	4732	4482	95,7	***	39,12	32,46	83,0	***	0,314	0,335	108,4	***
13												
14	4732	4281	91,4	**	39,61	28,28	72,3	**	0,345	0,335	108,4	**
15	4823	4536	96,9	***	40,53	33,81	86,5	***	0,319	0,335	108,4	***
16												
17	4675	4233	90,4	**	39,15	27,39	70,1	**	0,305	0,336	108,7	**
18	4762	4482	95,7	***	39,32	32,36	82,8	***	0,338	0,336	108,7	***
19												
20	4762	4305	91,9	**	38,22	26,73	68,4	**	0,322	0,349	112,9	**
21	4675	4482	95,7	***	39,22	31,89	81,6	***	0,307	0,341	110,4	***
22												
23	4646	4187		**	39,21	28,27		**	0,304	0,325		**
24	4618	4404		***	39,64	31,77		***	0,290	0,330		***
Mean of 1-24	4717				39,65				0,312			

* TESTED BEFORE HEATING

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE A.II.18 (contd.)

SPECIMEN SERIES : CCY

TEMPERATURE : 150°C

TREATMENT : DRYING DURING HEATING

INITIAL WATER CONTENT = 301 g = W_t

VIZ. W_c = 155,0 g = 51,5%
W_n = 80,0 g = 26,6%
W_g = 66,0 g = 21,9%

Spec. No.	DEFORMATION			COMPRESSIVE STRENGTH			WATER LOSS					HEAT TREATMENT
	Initial length mm	Strain ** mm/m	Strain *** mm/m	MPa	R.R %		Mass before heat A(g)	Mass after heat B(g)	$\frac{A-B}{W_t}$ %	Mass after wett. C(g)	$\frac{A-C}{W_t}$ %	
1	273,3			42,89			3924					No Heating. Tested at Room Temp.
2	270,9			39,28			3951					
3	270,9		42,55				3897					
Mean 1,2,3	271,7			41,52			3924					
4				41,55	101,0	*						Tested Imm. Max. Temp. Attained (Time T)
5	271,8	-0,21		41,69	101,4	**	3844	3642	68,2			
6	271,8	-0,21	-0,07	34,80	84,6	***	3851	3657	67,4	3838	4,3	
7				45,91	111,6	*						Tested At T + 12 hrs
8	272,8	-0,28		45,56	110,8	**	3955	3753	66,4			
9	274,3	-0,26	-0,04	32,82	79,8	***	3986	3772	69,8	3969	5,6	
10				43,67	106,2	*						Tested At T + 24 hrs
11	272,5	-0,28		43,58	106,0	**	3910	3698	70,4			
12	271,0	-0,26	-0,06	31,52	76,7	***	3880	3671	68,8	3860	6,6	
13				44,27	107,7	*						Tested At T + 36 hrs
14	272,0	-0,34		44,79	108,9	**	3934	3714	72,7			
15	273,3	-0,33	-0,08	30,84	75,0	***	3914	3691	74,1	3893	7,0	
16				46,51	113,1	*						Tested At T + 36 hrs + 1 cycle
17	272,5	-0,27		44,70	108,7	**	3944	3722	73,1			
18	270,5	-0,27	-0,05	32,04	77,9	***	3927	3724	67,1	3912	4,9	
19				45,30	110,2	*						Tested At T + 36 hrs + 2 Cycles
20	273,8	-0,32		44,96	109,3	**	3942	3715	74,8			
21	271,0	-0,28	-0,04	34,45	83,8	***	3881	3667	71,8	3863	6,0	
22						*						Tested At T + 36 hrs + 2 Cycles
23	271,0	-0,28		43,24		**	3903	3686	72,3			
24	272,3	-0,34	-0,07	30,15		***	3904	3684	73,3	3889	4,9	
Mean 1-24	272,3						3912					

* TESTED HOT

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE A.II.19

SPECIMEN SERIES : CCY

TEMPERATURE : 150°C

TREATMENT : DRYING DURING HEATING

Spec. No.	PULSE VELOCITY				DYNAMIC YOUNG'S MODULUS				POISSON'S RATIO			
	* m/sec	** and *** m/sec	R.R %		* GPa	** and *** GPa	R.R %		*	** and ***	R.R %	
1	4792				39,56				0,321			
2	4675				38,91				0,316			
3	4763				38,41				0,327			
Mean of 1,2,3	4733				38,96				0,321			
4												
5	4704	4257	90,9	**	39,38	30,90	79,0	**	0,306	0,305	98,7	**
6	4792	4482	95,7	***	38,87	34,97	89,4	***	0,322	0,313	101,3	***
7												
8	4733	4257	90,9	**	39,41	30,88	79,0	**	0,317	0,311	100,6	**
9	4675	4379	93,5	***	39,72	33,05	84,5	***	0,308	0,323	104,5	***
10												
11	4704	4141	88,4	**	38,41	30,10	77,0	**	0,319	0,296	95,8	**
12	4675	4405	94,1	***	38,47	33,54	85,8	***	0,313	0,317	102,6	***
13												
14	4618	4032	86,1	**	38,40	28,88	73,9	**	0,309	0,294	95,1	**
15	4675	4233	90,4	***	38,06	32,63	83,5	***	0,317	0,300	97,1	***
16												
17	4590	4075	87,0	**	40,24	28,73	73,5	**	0,288	0,303	98,1	**
18	4733	4430	94,6	***	37,74	34,42	88,0	***	0,330	0,318	102,9	***
19												
20	4646	4097	87,5	**	39,00	28,54	73,0	**	0,307	0,307	99,4	**
21	4675	4354	93,0	***	39,38	34,86	89,2	***	0,306	0,297	96,1	***
22												
23	4646	4164		**	39,28	29,09		**	0,304	0,312		**
24	4618	4379		***	37,35	32,66		***	0,315	0,323		***
Mean of 1-24	4677				38,83				0,312			

* TESTED BEFORE HEATING

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE A.II.19 (contd.)

SPECIMEN SERIES : CCY

TEMPERATURE : 250°C

TREATMENT : DRYING DURING HEATING

INITIAL WATER CONTENT = 301 g = W_t

VIZ. W_c = 155 g = 51,5%

W_n = 80 g = 26,6%

W_g = 66 g = 21,9%

Spec. No.	DEFORMATION			COMPRESSIVE STRENGTH			WATER LOSS					HEAT TREATMENT
	Initial length mm	Strain ** mm/m	Strain *** mm/m	MPa	R.R %		Mass before heat A(g)	Mass after heat B(g)	$\frac{A-B}{W_t}$ %	Mass after wett. C(g)	$\frac{A-C}{W_t}$ %	
1	270,4			42,55			3847					No Heating.
2	273,3			41,17			3945					Tested at
3	271,8			43,07			3947					Room Temp.
Mean 1,2,3	271,9			42,26			3913					
4				42,03	102,2	*						Tested Imm.
5	272,8	-0,09		40,48	98,4	**	3920	3691	76,8			Max. Temp.
6	271,0	-0,11	0,22	31,09	75,6	***	3847	3609	79,7	3829	6,0	Attained (Time T)
7				44,10	107,2	*						Tested At
8	273,6	-0,16		39,79	96,8	**	3954	3714	79,7			T + 12 hrs
9	271,5	-0,15	0,34	30,49	74,1	***	3935	3697	79,1	3919	5,3	
10				43,07	104,7	*						Tested At
11	272,8	-0,15		38,93	94,7	**	3936	3695	80,1			T + 24 hrs
12	273,3	-0,15	0,30	31,18	75,8	***	3932	3690	87,0	3916	5,3	
13				40,34	112,7	*						Tested At
14	273,3	-0,12		40,14	97,6	**	3945	3705	79,7			T + 36 hrs
15	274,3	-0,15	0,27	32,73	79,6	***	3931	3698	77,4	3925	5,3	
16				48,23	117,3	*						Tested At
17	271,3	-0,14		39,96	97,2	**	3916	3664	83,7			T + 36 hrs
18	271,8	-0,12	0,36	33,25	80,9	***	3950	3718	77,1	3935	5,0	+ 1 cycle
19				45,13	109,8	*						Tested At
20	271,5	-0,19		38,76	94,3	**	3947	3702	81,4			T + 36 hrs
21	271,0	-0,15	0,23	31,09	75,6	***	3868	3626	80,4	3850	6,0	+ 2 Cycles
22						*						Tested At
23	272,5	-0,19		36,95		**	3864	3606	85,7			T + 36 hrs
24	270,8	-0,15	0,24	32,73		***	3940	3713	75,4	3925	5,0	+ 2 Cycles
Mean 1-24	272,5						3920					

* TESTED HOT

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE A.II.20

SPECIMEN SERIES : CCY

TEMPERATURE : 250°C

TREATMENT : DRYING DURING HEATING

Spec. No.	PULSE VELOCITY				DYNAMIC YOUNG'S MODULUS				POISSON'S RATIO			
	* m/sec	** and *** m/sec	R.R %		* GPa	** and *** GPa	R.R %		*	** and ***	R.R %	
1	4732				27,94				0,323			
2	4704				38,28				0,321			
3	4704				39,01				0,317			
Mean of 1,2,3	4713				38,41				0,320			
4												
5	4675	3772	80,6	**	39,47	25,99	66,5	**	0,307	0,280	90,6	**
6	4732	4404	94,1	***	37,10	31,	79,3	***	0,329	0,357	109,1	***
7												
8	4618	3699	79,0	**	38,01	23,40	59,8	**	0,312	0,305	98,7	**
9	4732	4430	94,6	***	38,28	32,63	83,5	***	0,326	0,332	107,4	***
10												
11	4675	3699	79,0	**	38,20	22,93	58,6	**	0,318	0,311	100,6	**
12	4732	4482	95,7	***	38,13	33,02	84,5	***	0,325	0,334	108,1	***
13												
14	4646	3611	77,1	**	38,63	21,40	54,7	**	0,311	0,318	102,9	**
15	4762	4456	95,2	***	39,18	32,93	84,2	***	0,319	0,330	106,8	***
16												
17	4618	3611	77,1	**	38,20	20,14	51,5	**	0,310	0,334	108,1	**
18	4762	4536	96,9	***	39,11	33,62	86,0	***	0,324	0,338	109,4	***
19												
20	4704	3829	81,8	**	37,87	21,13	54,0	**	0,326	0,353	114,2	**
21	4675	4482	95,7	***	38,08	32,28	82,6	***	0,316	0,337	109,1	***
22												
23	4509	3577		**	35,99	19,30		**	0,308	0,335		**
24	4732	4563		***	38,49	33,18		***	0,325	0,344		***
Mean of 1-24	4684				38,20				0,318			

* TESTED BEFORE HEATING

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE A.II.20 (contd.)

SPECIMEN SERIES : CCY

TEMPERATURE : 400°C

TREATMENT : DRYING DURING HEATING

INITIAL WATER CONTENT = 301 g = W_t

VIZ. W_c = 155 g = 51,5%; W_n = 80 g = 26,6%; W_g = 66 g = 21,9%.

Spec. No.	DEFORMATION			COMPRESSIVE STRENGTH			WATER LOSS					HEAT TREATMENT
	Initial length mm	Strain ** mm/m	Strain *** mm/m	MPa	R.R %		Mass before heat A(g)	Mass after heat B(g)	$\frac{A-B}{W_t}$ %	Mass after wett. C(g)	$\frac{A-C}{W_t}$ %	
1	270,9			41,25			3883					No Heating.
2	274,0			40,22			3936					Tested at
3	270,4			38,17			3899					Room Temp.
Mean 1,2,3	271,8			39,88			3906					
4				40,48	98,4	*						Tested Imm.
5	272,3	0,21		37,21	90,5	**	3915	3680	78,1			Max. Temp.
6	270,5	0,24	0,94	33,94	82,5	***	3871	3634	78,7	3865	2,0	Attained (Time T)
7				40,05	97,4	*						Tested At
8	270,3	0,38		34,11	83,0	**	3894	3641	84,1			T + 12 hrs
9	272,0	1,02	1,75	32,64	79,4	***	3895	3653	80,4	3896	-0,3	
10				40,22	97,8	*						Tested At
11	273,3	0,54		30,49	74,1	**	3923	3662	86,7			T + 24 hrs
12	271,8	1,26	1,41	32,90	80,0	***	3884	3626	85,7	3877	2,3	
13				39,62	96,4	*						Tested At
14	271,5	0,60		31,01	75,4	**	3876	3620	85,0			T + 36 hrs
15	276,4	0,52	1,17	32,90	80,0	***	3879	3631	82,4	3873	2,0	
16				39,62	96,4	*						Tested At
17	270,5	1,69		35,14	85,5	**	3905	3668	78,7			T + 36 hrs
18	271,3	1,05	2,17	29,46	71,6	***	3866	3591	91,4	3868	-0,7	+ 1 cycle
19				41,03	102,2	*						Tested At
20	270,8	0,61		36,69	89,2	**	3903	3680	74,1			T + 36 hrs
21	270,8	0,26	0,90	33,42	81,3	***	3925	3693	77,1	3920	1,7	+ 2 Cycles
22						*						Tested At
23	269,7	1,15		37,12		**	3837	3591	81,7			T + 36 hrs
24	271,5	0,71	1,34	33,85		***	3936	3701	78,1	3931	1,7	+ 2 Cycles
Mean 1-24	271,5						3894					

* TESTED HOT

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE A.II.21

SPECIMEN SERIES : CCY

TEMPERATURE : 400 °C

TREATMENT : DRYING DURING HEATING

Spec. No.	PULSE VELOCITY				DYNAMIC YOUNG'S MODULUS				POISSON'S RATIO			
	* m/sec	** and *** m/sec	R.R %		* GPa	** and *** GPa	R.R %		*	** and ***	R.R %	
1	4618				39,17				0,299			
2	4675				40,29				0,299			
3	4733				41,03				0,303			
Mean of 1,2,3	4675				40,16				0,300			
4												
5	4646	3202	68,4	**	44,04	13,71	35,1	**	0,256	0,367	118,8	**
6	4704	4430	94,6	***	41,69	34,06	87,1	***	0,289	0,317	102,6	***
7												
8	4704	3036	64,8	**	41,57	11,31	28,9	**	0,293	0,382	123,6	**
9	4675	4405	94,1	***	41,63	33,75	86,3	***	0,285	0,317	102,6	***
10												
11	4590	2875	61,4	**	34,60	10,45	26,7	**	0,334	0,376	121,7	**
12	4675	4354	93,0	***	34,26	32,90	84,1	***	0,345	0,317	102,6	***
13												
14	4704	2751	58,8	**	39,08	6,13	15,7	**	0,311	0,430	139,2	**
15	4704	4330	92,5	***	40,76	35,67	91,2	***	0,290	0,277	89,6	***
16												
17	4618	2729	58,3	**	41,84	6,40	16,4	**	0,276	0,380	123,0	**
18	4590	4281	91,4	***	37,87	31,17	79,7	***	0,305	0,323	104,5	***
19												
20	4704	3060	65,4	**	41,39	10,45	26,7	**	0,295	0,397	128,5	**
21	4733	4536	96,9	***	42,65	38,78	94,1	***	0,290	0,312	101,0	***
22												
23	4618			**	39,70	6,92		**	0,292			**
24	4618	2741		***	41,66	33,79		***	0,280	0,297		***
Mean of 1-24	4663				40,20				0,296			

* TESTED BEFORE HEATING

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE A.II.21 (contd.)

SPECIMEN SERIES : BMY

TEMPERATURE : 70°C

TREATMENT : SATURATED DURING HEATING

INITIAL WATER CONTENT = 531 g = W_t

VIZ. W_c = 235 g = 44,3%

W_n = 162 g = 30,5%

W_g = 134 g = 25,2%

Spec. No.	DEFORMATION			COMPRESSIVE STRENGTH		WATER LOSS					HEAT TREATMENT
	Initial length mm	Strain ** mm/m	Strain *** mm/m	MPa	R.R %	Mass before heat A(g)	Mass after heat B(g)	$\frac{A-B}{W_t}$ %	Mass after wett. C(g)	$\frac{A-C}{W_t}$ %	
1	272,8			48,06		3703					No Heating.
2	272,3			48,57		3669					Tested at
3	271,3			47,38		3661					Room Temp.
Mean 1,2,3	272,0			48,00		3678					
4				39,60	84,3 *						Tested Imm.
5	271,5	0,04		47,05	100,1 **	3634	3634	0,0			Max. Temp. Attained
6	272,8	0,06	0,06	48,99	104,2 ***	3719	3719	0,0	3729	0,0	(Time T)
7				38,59	82,1 *						Tested At
8	272,3	0,05		41,46	88,2 **	3710	3710	0,0			T + 12 hrs
9	271,8	0,08	0,06	43,91	93,4 ***	3646	3645	0,2	3645	0,2	
10				37,91	80,7 *						Tested At
11	272,8	0,10		44,34	94,3 **	3710	3708	0,4			T + 24 hrs
12	270,3	0,09	0,08	43,66	92,9 ***	3677	3676	0,2	3677	0,0	
13				42,65	90,7 *						Tested At
14	272,0	0,11		45,52	96,9 **	3673	3672	0,2			T + 36 hrs
15	273,1	0,12	0,10	45,44	96,7 ***	3619	3617	0,4	3617	0,4	
16				40,96	87,1 *						Tested At
17	272,3	0,13		42,20	98,3 **	3646	3644	0,4			T + 36 hrs
18	271,3	0,12	0,10	42,56	90,6 ***	3671	3671	0,0	3670	0,2	+ 1 cycle
19				40,78	86,8 *						Tested At
20	272,0	0,19		42,73	90,9 **	3699	3696	0,6			T + 36 hrs
21	271,5	0,12	0,10	46,79	99,6 ***	3652	3650	0,4	3650	0,4	+ 2 Cycles
22					*						Tested At
23	272,5	0,14		43,24	**	3682	3674	1,5			T + 36 hrs
24	272,3	0,17	0,16	46,37	***	3641	3641	0,0	3640	0,2	+ 2 Cycles
Mean 1-24	272,0					3671					

* TESTED HOT

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE A.II.22

SPECIMEN SERIES : BMY

TEMPERATURE : 70°C

TREATMENT : SATURATED DURING HEATING

Spec. No.	PULSE VELOCITY				DYNAMIC YOUNG'S MODULUS				POISSON'S RATIO			
	* m/sec	** and *** m/sec	R.R %		* GPa	** and *** GPa	R.R %		*	** and ***	R.R %	
1	4119				29,07				0,305			
2	4141				29,86				0,296			
3	4141				29,31				0,304			
Mean of 1,2,3	4135				29,41				0,302			
4												
5	4119	4097	99,5	**	29,12	28,13	96,3	**	0,299	0,323	110,2	**
6	4075	4097	99,5	***	29,28	29,28	100,3	***	0,297	0,30	102,4	***
7												
8	4141	4097	99,5	**	30,01	27,89	95,5	**	0,299	0,316	107,8	**
9	4075	4075	98,9	***	29,15	28,34	97,1	***	0,292	0,30	102,4	***
10												
11	4119	4053	98,4	**	29,68	28,20	96,6	**	0,298	0,305	104,1	**
12	4119	4075	98,9	***	29,23	28,15	96,4	***	0,304	0,30	102,4	***
13												
14	4119	4075	98,9	**	29,48	27,76	95,1	**	0,298	0,311	106,1	**
15	4075	4032	97,9	***	28,62	26,25	89,9	***	0,294	0,31	102,4	***
16												
17	4119	4075	98,9	**	29,49	27,66	94,7	**	0,295	0,309	105,5	**
18	4119	4075	98,9	***	29,01	28,02	96,0	***	0,304	0,30	102,4	***
19												
20	4097	3990	96,9	**	28,77	27,01	92,7	**	0,305	0,308	105,1	**
21	4141	4075	98,9	***	29,17	28,25	96,7	***	0,304	0,304	102,4	***
22												
23	4119	4011		**	29,71	27,57		**	0,295	0,302		**
24	4097	4032		***	28,53	28,18		***	0,302	0,295		***
Mean of 1-24	4110				28,99				0,299			

* TESTED BEFORE HEATING

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE A.II.22 (contd.)

SPECIMEN SERIES : BMY

TEMPERATURE : 100°C

TREATMENT : SATURATED DURING HEATING

INITIAL WATER CONTENT = 531 g = W_t

VIZ. W_c = 235 g = 44,3%
W_n = 162 g = 30,5%
W_g = 134 g = 25,2%

Spec. No.	DEFORMATION			COMPRESSIVE STRENGTH			WATER LOSS					HEAT TREATMENT
	Initial length mm	Strain ** mm/m	Strain *** mm/m	MPa	R.R %		Mass before heat A(g)	Mass after heat B(g)	$\frac{A-B}{W_t}$ %	Mass after wett. C(g)	$\frac{A-C}{W_t}$ %	
1	271,5			47,89			3686					No Heating.
2	273,3			46,16			3721					Tested at
3	273,3			48,41			3682					Room Temp.
Mean 1,2,3	272,7			47,49			3696					
4				35,92	76,4	*						Tested Imm. Max. Temp. Attained (Time T)
5	271,5	0,09		39,71	84,5	**	3694	3695	-0,2			
6	271,8	0,11	0,10	44,27	94,2	***	3638	3637	0,2	3637	0,2	
7				38,76	82,5	*						Tested At
8	272,3	0,14		39,45	83,9	**	3687	3684	0,6			T + 12 hrs
9	272,8	0,13	0,11	43,07	91,6	***	3688	3684	0,8	3684	0,8	
10				39,28	83,6	*						Tested At
11	270,5	0,14		39,88	84,9	**	3651	3647	0,8			T + 24 hrs
12	271,3	0,15	0,13	42,20	89,8	***	3684	3682	0,4	3682	0,4	
13				36,61	77,9	*						Tested At
14	271,5	0,16		42,89	91,3	**	3722	3718	0,8			T + 36 hrs
15	271,8	0,13	0,13	43,58	92,7	***	3664	3659	0,9	3660	0,8	
16				39,19	83,4	*						Tested At
17	271,5	0,15		43,41	92,4	**	3727	3722	0,9			T + 36 hrs
18	273,6	0,15	0,14	42,55	90,5	***	3734	3732	0,4	3733	0,2	+ 1 cycle
19				41,35	88,0	*						Tested At
20	272,3	0,17		44,10	93,8	**	3626	3623	0,6			T + 36 hrs
21	272,0	0,14	0,14	42,72	90,9	***	3655	3653	0,4	3652	0,6	+ 2 Cycles
22						*						Tested At
23	274,3	0,17		42,89		**	3687	3672	2,0			T + 36 hrs
24	270,5	0,22	0,20	41,17		***	3688	3679	1,7	3684	0,8	+ 2 Cycles
Mean 1-24	272,0						3682					

* TESTED HOT

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE A.II.23

SPECIMEN SERIES : BMY

TEMPERATURE : 100°C

TREATMENT : SATURATED DURING HEATING

Spec. No.	PULSE VELOCITY				DYNAMIC YOUNG'S MODULUS				POISSON'S RATIO			
	* m/sec	** and *** m/sec	R.R %		* GPa	** and *** GPa	R.R %		*	** and ***	R.R %	
1	4119				29,07				0,305			
2	4119				29,27				0,303			
3	4119				19,14				0,301			
Mean of 1,2,3	4119				19,16				0,303			
4												
5	4075	3908	94,9	**	29,33	36,50	90,8	**	0,295	0,301	102,7	**
6	4053	3990	96,9	***	28,35	27,02	92,5	***	0,297	0,303	103,4	***
7												
8	4075	3735	90,7	**	29,35	25,14	86,1	**	0,293	0,285	97,3	**
9	4075	3908	94,9	***	29,14	26,06	89,2	***	0,295	0,304	103,8	***
10												
11	4053	3755	90,7	**	29,14	24,71	84,6	**	0,290	0,290	99,0	**
12	4075	3908	94,9	***	29,11	25,67	87,9	***	0,297	0,311	106,1	***
13												
14	4011	3699	89,9	**	29,44	25,00	85,6	**	0,284	0,284	96,9	**
15	4119	3928	95,4	***	28,56	25,54	87,5	***	0,291	0,313	106,8	***
16												
17	4053	3735	90,7	**	29,59	25,56	87,5	**	0,291	0,283	96,6	**
18	4075	3888	94,4	***	28,84	25,51	87,4	***	0,302	0,311	106,1	***
19												
20	4075	3735	90,7	**	28,42	24,33	83,3	**	0,298	0,291	99,3	**
21	4141	3908	94,9	***	28,96	26,07	89,3	***	0,306	0,302	103,1	***
22												
23	4119	3888		**	29,29	26,06		**	0,299	0,290		**
24	4097	3928		***	29,44	26,75		***	0,298	0,302		***
Mean of 1-24	4078				29,07				0,295			

* TESTED BEFORE HEATING

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE A.II.23 (contd.)

SPECIMEN SERIES : BMY

TEMPERATURE : 70°C

TREATMENT : DRYING DURING HEATING

INITIAL WATER CONTENT = 531 g = W_t

VIZ. W_c = 235 g = 44,3%; W_n = 162 g = 30,5%; W_g = 134 g = 25,2%

Spec. No.	DEFORMATION			COMPRESSIVE STRENGTH			WATER LOSS					HEAT TREATMENT
	Initial length mm	Strain ** mm/m	Strain *** mm/m	MPa	R.R %		Mass before heat A(g)	Mass after heat B(g)	$\frac{A-B}{W_t}$ %	Mass after wett. C(g)	$\frac{A-C}{W_t}$ %	
1	270,9			45,02			3610					No Heating.
2	272,9			46,17			3667					Tested at
3	272,8			48,06			3667					Room Temp.
Mean 1,2,3	272,2			46,68			3648					
4				41,69	88,7	*						Tested Imm.
5	272,0	-0,32		48,84	103,9	**	3551	3472	14,9			Max. Temp.
6	274,6	-0,35	-0,10	46,94	99,9	***	3626	3540	16,2	3601	4,7	Attained (Time T)
7				40,48	86,1	*						Tested At
8	272,0	-0,32		48,41	103,0	**	3535	3419	21,8			T + 12 hrs
9	272,0	-0,35	-0,10	45,65	97,1	***	3598	3471	23,9	3572	4,9	
10				45,82	97,5	*						Tested At
11	270,8	-0,35		51,51	109,6	**	3662	3522	26,4			T + 24 hrs
12	272,3	-0,37	-0,10	42,63	90,7	***	3596	3551	27,3	3571	4,7	
13				46,17	98,2	*						Tested At
14	271,3	-0,38		51,60	110,0	**	3553	3400	28,8			T + 36 hrs
15	273,3	-0,41	-0,14	49,61	105,6	***	3641	3485	29,4	3615	4,8	
16				46,51	99,0	*						Tested At
17	272,5	-0,38		52,28	111,2	**	3725	3561	30,9			T + 36 hrs
18	272,5	-0,44	-0,20	40,65	86,5	***	3629	3469	30,1	3599	5,6	+ 1 cycle
19				49,44	105,2	*						Tested At
20	273,1	-0,44		48,92	104,1	**	3680	3507	32,6			T + 36 hrs
21	272,3	-0,44	-0,14	43,41	92,4	***	3564	3390	32,8	3535	5,5	+ 2 Cycles
22						*						Tested At
23	272,0	-0,48		50,73		**	3586	3415	32,2			T + 36 hrs
24	273,6	-0,48	-0,17	43,84		***	3617	3450	33,3	3603	4,5	+ 2 Cycles
Mean 1-24	272,5						3612					

* TESTED HOT

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE A.II.24

SPECIMEN SERIES : BMY

TEMPERATURE : 70°C

TREATMENT : DRYING DURING HEATING

Spec. No.	PULSE VELOCITY				DYNAMIC YOUNG'S MODULUS				POISSON'S RATIO			
	* m/sec	** and *** m/sec	R.R %		* GPa	** and *** GPa	R.R %		*	** and ***	R.R %	
1	4119				30,02				0,286			
2	4119				29,84				0,292			
3	4141				30,28				0,290			
Mean of 1,2,3	4126				30,05				0,289			
4												
5	4119	3990	96,9	**	29,05	27,34	93,6	**	0,291	0,281	95,9	**
6	4141	4075	98,9	***	29,94	29,46	100,9	***	0,288	0,278	94,9	***
7												
8	4017	3791	92,0	**	28,39	25,77	88,3	**	0,278	0,253	86,3	**
9	4141	4053	98,4	***	29,83	29,09	99,6	***	0,290	0,280	95,6	***
10												
11	4187	3948	95,8	**	31,36	27,26	93,4	**	0,287	0,281	95,9	**
12	4141	4032	97,9	***	29,35	27,97	95,8	***	0,295	0,290	99,0	***
13												
14	4075	3829	93,0	**	29,38	25,23	86,4	**	0,279	0,272	92,8	**
15	4187	4053	98,4	***	30,88	28,86	98,8	***	0,288	0,286	97,6	***
16												
17	4164	3888	94,4	**	31,32	27,31	93,5	**	0,288	0,269	91,8	**
18	4141	4032	97,9	***	30,88	28,13	96,3	***	0,278	0,291	99,3	***
19												
20	4164	3848	93,4	**	30,91	26,61	91,1	**	0,287	0,263	89,8	**
21	4164	3990	96,9	***	29,58	27,17	93,0	***	0,293	0,290	99,0	***
22												
23	4119	3848		**	29,33	25,33		**	0,291	0,275		**
24	4075	3969		***	29,30	27,83		***	0,285	0,282		***
Mean of 1-24	4131				29,93				0,288			

* TESTED BEFORE HEATING

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE A.II.24 (contd.)

SPECIMEN SERIES : BMY

TEMPERATURE : 100°C

TREATMENT : DRYING DURING HEATING

INITIAL WATER CONTENT = 531 g = W_t

VIZ. W_c = 235 g = 44,3%; W_n = 162 g = 30,5%; W_g = 134 g = 25,2%

Spec. No.	DEFORMATION			COMPRESSIVE STRENGTH			WATER LOSS					HEAT TREATMENT
	Initial length mm	Strain ** mm/m	Strain *** mm/m	MPa	R.R %		Mass before heat A(g)	Mass after heat B(g)	$\frac{A-B}{W_t}$ %	Mass after wett. C(g)	$\frac{A-C}{W_t}$ %	
1	271,6			46,60			3629					No Heating.
2	273,9			47,80			3661					Tested at
3	274,1			47,03			3627					Room Temp.
Mean 1,2,3	273,2			47,14			3639					
4				38,24	81,4	*						Tested Imm.
5	271,8	-0,21		43,24	92,0	**	3631	3482	28,1			Max. Temp.
6	272,8	-0,22	-0,02	42,89	91,3	***	3613	3466	27,7	3591	4,1	Attained (Time T)
7				43,07	91,6	*						Tested At
8	272,5	-0,37		43,07	91,6	**	3661	3424	44,6			T + 12 hrs
9	272,8	-0,41	-0,15	41,51	88,3	***	3630	3365	49,9	3604	4,8	
10				40,65	86,5	*						Tested
11	274,3	-0,50		44,36	94,4	**	3665	3374	54,8			T + 24 hrs
12	273,6	-0,48	-0,18	41,51	88,3	***	3659	3376	53,3	3618	5,8	
13				44,44	94,6	*						Tested At
14	273,8	-0,54		46,34	98,6	**	3620	3317	57,1			T + 36 hrs
15	271,5	-0,58	-0,22	38,24	81,4	***	3645	3342	57,1	3618	5,1	
16				46,51	99,0	*						Tested At
17	274,6	-0,59		48,75	103,7	**	3642	3312	62,1			T + 36 hrs
18	275,6	-0,57	-0,22	42,81	91,1	***	3683.	3371	58,8	3654	5,5	+ 1 cycle
19				44,62	94,9	*						Tested At
20	272,5	-0,60		49,61	105,6	**	3637	3322	59,3			T + 36 hrs
21	273,1	-0,62	-0,21	39,96	85,0	***	3655	3334	60,5	36,27	5,3	+ 2 Cycles
22						*						Tested At
23	272,5	-0,71		52,37		**	3660	3319	64,2			T + 36 hrs
24	272,8	-0,60	-0,26	35,75		***	3664	3333	62,3	3633	5,8	+ 2 Cycles
Mean 1-24	273,1						3648					

* TESTED HOT

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE A.II.25

SPECIMEN SERIES : BMY

TEMPERATURE : 100°C

TREATMENT : DRYING DURING HEATING

Spec. No.	PULSE VELOCITY				DYNAMIC YOUNG'S MODULUS				POISSON'S RATIO			
	* m/sec	** and *** m/sec	R.R %		* GPa	** and *** GPa	R.R %		*	** and ***	R.R %	
1	4187				30,16				0,298			
2	4233				29,79				0,310			
3	4187				29,42				0,303			
Mean of 1,2,3	4202				29,79				0,304			
4												
5	4187	3717	90,2	**	29,97	25,64	87,8	**	0,300	0,245	83,6	**
6	4187	3928	95,4	***	29,43	26,51	90,8	***	0,303	0,293	100,0	***
7												
8	4187	3681	89,4	**	29,52	24,13	82,6	**	0,307	0,257	87,7	**
9	4210	3772	91,6	***	29,36	24,75	84,8	***	0,310	0,290	99,0	***
10												
11	4210	3577	86,8	**	29,78	23,30	79,8	**	0,306	0,232	79,2	**
12	4164	3699	89,8	***	30,21	24,54	84,0	***	0,293	0,278	94,9	***
13												
14	4187	3594	87,3	**	29,74	23,24	79,6	**	0,299	0,230	78,5	**
15	4164	3717	90,2	***	29,65	24,00	82,2	***	0,302	0,293	100,0	***
16												
17	4164	3579	86,9	**	29,60	22,86	78,3	**	0,298	0,232	79,2	**
18	4164	3663	88,9	***	30,01	24,20	82,9	***	0,296	0,276	94,2	***
19												
20	4187	3594	87,3	**	30,55	22,69	77,7	**	0,293	0,248	84,6	**
21	4164	3663	88,9	***	30,55	23,71	81,2	***	0,289	0,285	97,3	***
22												
23	4187	3594		**	30,21	23,07		**	0,299	0,238		**
24	4164	3611		***	30,72	23,85		***	0,289	0,272		***
Mean of 1-24	4180				29,95				0,299			

* TESTED BEFORE HEATING

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE A.II.25 (contd.)

SPECIMEN SERIES : BMY

TEMPERATURE : 150°C

TREATMENT : DRYING DURING HEATING

INITIAL WATER CONTENT = 531 g = W_t

VIZ. W_c = 235 g = 44,3%

W_n = 162 g = 30,5%

W_g = 134 g = 25,2%

Spec. No.	DEFORMATION			COMPRESSIVE STRENGTH			WATER LOSS					HEAT TREATMENT
	Initial length mm	Strain ** mm/m	Strain *** mm/m	MPa	R.R %		Mass before heat A(g)	Mass after heat B(g)	$\frac{A-B}{W_t}$ %	Mass after wett. C(g)	$\frac{A-C}{W_t}$ %	
1	271,9			46,85			3583					No Heating. Tested at Room Temp.
2	272,9			47,37			3631					
3	273,0			44,96			3634					
Mean 1,2,3	272,6			46,34			3616					
4				37,21	79,2	*						Tested Imm. Max. Temp. Attained (Time T)
5	273,3	-0,40		41,51	88,3	**	3579	3330	45,2			
6	273,1	-0,45	-0,0	39,10	83,2	***	3543	3309	41,4	3513	5,6	
7				43,41	92,4	*						Tested At T + 12 hrs
8	272,0	-0,56		43,07	91,6	**	3581	3222	67,6			
9	271,8	-0,57	-0,05	29,28	62,3	***	3633	3258	70,6	3598	6,6	
10				52,37	111,4	*						Tested At T + 24 hrs
11	273,8	-0,65		42,38	90,2	**	3521	3159	70,4			
12	274,3	-0,62	-0,10	26,53	56,4	***	3623	3253	69,7	3588	6,6	
13				43,75	93,1	*						Tested At T + 36 hrs
14	273,3	-0,78		44,79	95,3	**	3595	3221	70,4			
15	271,8	-0,73	-0,13	27,22	57,9	***	3642	3270	70,1	3611	5,8	
16				48,75	103,7	*						Tested At T + 36 hrs + 1 cycle
17	272,5	-0,73		49,27	104,8	**	3567	3187	71,6			
18	271,8	-0,81	-0,07	33,59	71,5	***	3574	3197	71,0	3536	7,2	
19				49,44	105,2	*						Tested At T + 36 hrs + 2 Cycles
20	273,6	-0,86		51,51	109,6	**	3642	3260	71,9			
21	270,5	-0,75	-0,08	33,42	71,1	***	3652	3270	71,9	3613	7,3	
22						*						Tested At T + 36 hrs + 2 Cycles
23	271,5	-0,87		49,27		**	3563	3186	71,0			
24	269,0	-0,82	-0,15	35,14		***	3585	3211	70,4	3551	6,4	
Mean 1-24	272,3						3589					

* TESTED HOT

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE A.II.26

SPECIMEN SERIES : BMY

TEMPERATURE : 150°C

TREATMENT : DRYING DURING HEATING

Spec. No.	PULSE VELOCITY				DYNAMIC YOUNG'S MODULUS				POISSON'S RATIO			
	* m/sec	** and *** m/sec	R.R %		* GPa	** and *** GPa	R.R %		*	** and ***	R.R %	
1	4011				27,63				0,293			
2	4032				28,12				0,294			
3	4032				28,07				0,295			
Mean of 1,2,3	4025				27,94				0,294			
4												
5	4032	3432	83,3	**	27,35	19,71	67,5	**	0,299	0,272	92,8	**
6	4053	3646	88,5	***	27,88	22,06	75,5	***	0,292	0,297	101,4	***
7												
8	4032	3387	82,2	**	27,52	29,40	66,4	**	0,298	0,253	86,3	**
9	3969	3512	85,3	***	28,23	20,08	68,8	***	0,283	0,314	107,2	***
10												
11	4011	3313	80,4	**	27,52	18,14	62,1	**	0,285	0,251	85,7	**
12	3990	3528	85,7	***	28,05	19,46	66,6	***	0,284	0,322	109,9	***
13												
14	3990	3299	80,1	**	27,33	18,17	62,2	**	0,293	0,257	87,7	**
15	4032	3544	86,0	***	27,32	20,18	69,1	***	0,307	0,319	108,9	***
16												
17	4032	3299	80,1	**	27,80	18,03	61,7	**	0,292	0,257	87,7	**
18	4053	3528	85,7	***	27,80	20,09	68,8	***	0,298	0,314	107,2	***
19												
20	3928	3270	79,4	**	28,07	28,59	63,7	**	0,274	0,241	82,3	**
21	3969	3495	84,9	***	28,40	20,66	70,8	***	0,284	0,304	103,8	***
22												
23	3990	3328		**	27,64	17,94		**	0,287	0,269		**
24	3990	3544		***	28,10	20,41		***	0,287	0,313		***
Mean of 1-24	4006				27,69				0,290			

* TESTED BEFORE HEATING

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE A.II.26 (contd.)

SPECIMEN SERIES : BMY

TEMPERATURE : 250°C

TREATMENT : DRYING DURING HEATING

INITIAL WATER CONTENT = 531 g = W_t

VIZ. W_c = 235 g = 44,3%; W_n = 162 g = 30,5%; W_g = 134 g = 25,2%

Spec. No.	DEFORMATION			COMPRESSIVE STRENGTH			WATER LOSS					HEAT TREATMENT
	Initial length mm	Strain ** mm/m	Strain *** mm/m	MPa	R.R %		Mass before heat A(g)	Mass after heat B(g)	$\frac{A-B}{W_t}$ %	Mass after wett. C(g)	$\frac{A-C}{W_t}$ %	
1	270,2			47,89			3587					No Heating.
2	271,4			45,30			3589					Tested at
3	272,6			44,96			3651					Room Temp.
Mean 1,2,3	271,4			46,05								
4				47,54	101,1	*						Tested Imm.
5	270,8	-0,19		39,45	83,9	**	3547	3165	71,9			Max. Temp.
6	271,3	-0,29	0,66	31,87	67,8	***	3625	3233	73,8	3589	6,8	Attained (Time T,
7				47,37	100,8	*						Tested At
8	270,0	-0,28		44,79	95,3	**	3579	3194	72,5			T + 12 hrs
9	271,3	-0,28	0,55	30,31	64,5	***	3541	3144	74,8	3518	4,3	
10				43,93	93,5	*						Tested At
11	270,8	-0,27		40,14	85,4	**	3605	3211	74,2			T + 24 hrs
12	270,3	-0,32	0,77	31,87	67,8	***	3581	3193	73,3	3548	6,2	
13				47,03	100,1	*						Tested At
14	270,3	-0,36		44,10	93,8	**	3585	31,93	73,8			T + 36 hrs
15	271,8	-0,48	0,62	32,38	68,9	***	3593	3198	74,4	3558	6,6	
16				46,68	99,3	*						Tested At
17	269,7	-0,46		44,44	94,6	**	3593	3186	76,6			T + 36 hrs
18	271,0	-0,45	0,73	30,83	65,6	***	3629	3221	76,8	3593	6,8	+ 1 cycle
19				44,96	95,7	*						Tested At
20	269,7	-0,48		45,48	96,8	**	3651	3242	77,0			T + 36 hrs
21	270,8	-0,43	0,63	33,59	71,5	***	3624	3231	74,0	3587	7,0	+ 2 Cycles
22						*						Tested At
23	269,7	-0,62		43,58		**	3598	3192	76,5			T + 36 hrs
24	273,6	-0,68	0,37	31,18		***	3626	3229	74,8	3594	6,0	+ 2 Cycles
Mean 1-24	270,8						3592					

* TESTED HOT

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE A.II.27

SPECIMEN SERIES : BMY

TEMPERATURE : 250°C

TREATMENT : DRYING DURING HEATING

Spec. No.	PULSE VELOCITY				DYNAMIC YOUNG'S MODULUS				POISSON'S RATIO			
	* m/sec	** and *** m/sec	R.R %		* GPa	** and *** GPa	R.R %		*	** and ***	R.R %	
1	4187				26,85				0,332			
2	4187				28,12				0,318			
3	4187				27,61				0,316			
Mean of 1,2,3	4187				27,53				0,322			
4												
5	4187	2702	65,6	**	27,03	13,92	47,7	**	0,326	0,150	51,2	**
6	4187	3512	85,3	***	28,64	20,57	70,4	***	0,315	0,305	104,1	***
7												
8	4164	2886	70,1	**	27,37	15,67	53,7	**	0,323	0,177	60,4	**
9	4141	3561	86,5	***	26,78	21,45	73,5	***	0,322	0,293	100,0	***
10												
11	4187	2875	69,8	**	27,13	14,36	49,2	**	0,330	0,238	81,2	**
12	4164	3544	86,0	***	26,98	21,26	72,8	***	0,327	0,297	101,4	***
13												
14	4164	2897	70,3	**	26,98	15,00	51,4	**	0,327	0,218	74,4	**
15	4187	3561	86,5	***	26,97	21,81	74,7	***	0,330	0,290	99,0	***
16												
17	4187	2771	67,3	**	27,45	13,88	47,5	**	0,327	0,210	71,7	**
18	4210	3561	86,5	***	27,25	21,81	74,7	***	0,333	0,295	100,7	***
19												
20	4164	2920	70,9	**	27,54	15,48	53,0	**	0,327	0,219	74,7	**
21	4210	3561	86,5	***	27,88	22,09	75,7	***	0,327	0,290	99,0	***
22												
23	4164	3012		**	26,37	15,21		**	0,335	0,257		**
24	4141	3561		***	27,40	21,74		***	0,319	0,293		***
Mean of 1-24	4176				27,22				0,326			

* TESTED BEFORE HEATING

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE A.II.27 (contd.)

SPECIMEN SERIES : BMY

TEMPERATURE : 400°C.

TREATMENT : DRYING DURING HEATING

INITIAL WATER CONTENT = 531 g = W_t

VIZ. W_c = 235 g = 44,3%
W_n = 162 g = 30,5%
W_g = 134 g = 25,2%

Spec. No.	DEFORMATION			COMPRESSIVE STRENGTH			WATER LOSS					HEAT TREATMENT
	Initial length mm	Strain ** mm/m	Strain *** mm/m	MPa	R.R %		Mass before heat A(g)	Mass after heat B(g)	$\frac{A-B}{W_t}$ %	Mass after wett. C(g)	$\frac{A-C}{W_t}$ %	
1	270,9			46,68			3627					No Heating. Tested at Room Temp.
2	272,6			47,29			3591					
3	270,7			47,89			3581					
Mean 1,2,3	271,4			47,29			3600					
4				44,10	93,8	*						Tested Imm. Max. Temp. Attained (Time T)
5	271,8	1,44		30,49	64,9	**	3566	3154	81,2			
6	270,8	1,29	2,70	31,87	67,8	***	3602	3186	81,9	3582	3,8	
7				45,30	96,4	*						Tested At T + 12 hrs
8	272,0	1,17		33,25	70,7	**	3636	3219	82,1			
9	272,0	2,10	2,87	32,30	68,9	***	3629	3204	84,6	3621	1,5	
10				40,48	86,1	*						Tested At T + 24 hrs
11	270,5	1,81		29,97	63,8	**	3545	3124	83,2			
12	271,8	1,46	2,84	30,49	64,9	***	3580	3158	83,6	3565	2,8	
13				39,96	85,0	*						Tested At T + 36 hrs
14	272,8	1,95		30,49	64,9	**	3594	3174	83,6			
15	271,0	1,17	2,55	32,04	68,2	***	3586	3165	83,1	3575	2,1	
16				42,89	91,3	*						Tested At T + 36 hrs + 1 cycle
17	269,7	2,29		28,85	61,4	**	3609	3175	85,9			
18	270,5	1,69	3,22	31,01	66,0	***	3573	3150	79,7	3564	1,7	
19				42,20	89,8	*						Tested At T + 36 hrs + 2 Cycles
20	269,2	0,80		29,97	63,8	**	3540	3122	78,7			
21	269,2	0,89	2,36	33,25	70,7	***	3571	3154	78,5	3554	3,2	
22						*						Tested At T + 36 hrs + 2 Cycles
23	271,0	1,47		32,04		**	3589					
24						***						
Mean 1-24												

* TESTED HOT

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE A.II.28

SPECIMEN SERIES : BMY

TEMPERATURE : 400°C

TREATMENT : DRYING DURING HEATING

Spec. No.	PULSE VELOCITY				DYNAMIC YOUNG'S MODULUS				POISSON'S RATIO			
	* m/sec	** and *** m/sec	R.R %		* GPa	** and *** GPa	R.R %		*	** and ***	R.R %	
1	4164				32,54				0,262			
2	4210				32,04				0,272			
3	4141				31,90				0,260			
Mean of 1,2,3	4173				32,16				0,265			
4												
5	4075	2093	50,8	**	31,87	8,11	27,8	**	0,239	0,174	59,4	**
6	4141	3772	91,6	***	32,91	25,86	88,6	***	0,247	0,270	92,2	***
7												
8	4210	2215	53,8	**	33,38	8,29	28,4	**	0,260	0,253	86,3	**
9	4187	38,29	93,0	***	33,22	27,46	94,0	***	0,255	0,260	88,7	***
10												
11	4075	2071	50,3	**	32,8	7,37	25,2	**	0,221	0,229	78,2	**
12	4075	3754	91,1	***	31,58	24,73	84,7	***	0,247	0,283	96,6	***
13												
14	4187	2059	50,0	**	32,9	6,17	21,1	**	0,254	0,308	105,1	**
15	4187	3928	95,4	***	32,36	27,01	92,5	***	0,264	0,286	97,6	***
16												
17	4141	1979	48,0	**	32,41	5,76	19,7	**	0,258	0,308	105,1	**
18	4164	3908	94,9	***	32,63	26,71	91,5	***	0,254	0,286	97,6	***
19												
20	4164	2037	49,5	**	31,98	7,51	25,7	**	0,262	0,194	66,2	**
21	4187	3848	93,4	***	33,22	22,84	78,2	***	0,252	0,329	112,3	***
22												
23	4164	1984		**	31,93	6,66		**	0,271	0,250		**
24	4164	3848		***	32,13	22,51		***	0,260	0,332		***
Mean of 1-24	4152				32,52				0,253			

* TESTED BEFORE HEATING

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE A.II.28 (contd.)

SPECIMEN SERIES : CMX

TEMPERATURE : 70°C

TREATMENT : SATURATED DURING HEATING

INITIAL WATER CONTENT = 592 g = W_t

VIZ. W_c = 304 g = 51,3%; W_n = 158 g = 24,7%; W_g = 130 g = 22,0%

Spec. No.	DEFORMATION			COMPRESSIVE STRENGTH			WATER LOSS					HEAT TREATMENT
	Initial length mm	Strain ** mm/m	Strain *** mm/m	MPa	R.R %		Mass before heat A(g)	Mass after heat B(g)	$\frac{A-B}{W_t}$ %	Mass after wett. C(g)	$\frac{A-C}{W_t}$ %	
1	273,3			40,31			3610					No Heating.
2	271,8			41,51			3594					Tested at
3	271,3			40,14			3598					Room Temp.
Mean 1,2,3	272,1			40,65			3601					
4					92,3	*						Tested Imm. Max. Temp. Attained (Time T)
5	273,1	0,08		38,16	95,5	**	3616	3614	0,3			
6	271,5	0,08	0,06	39,96	100,0	***	3601	3601	0,0	3604	-0,5	
7				33,16	83,0	*						Tested At T + 12 hrs
8	270,5	0,09		37,90	94,9	**	3598	3594	0,7			
9	272,3	0,10	0,09	36,00	90,1	***	3555	3552	0,5	3556	-0,2	
10				36,69	91,8	*						Tested At T + 24 hrs
11	274,1	0,11		37,04	92,7	**	3628	3625	0,5			
12	271,0	0,13	0,13	38,76	97,0	***	3594	3592	0,3	3593	0,2	
13				35,92	89,9	*						Tested At T + 36 hrs
14	273,3	0,14		36,86	92,3	**	3638	3633	0,9			
15	270,3	0,12	0,12	37,90	94,9	***	3630	3625	0,9	3628	0,3	
16				33,59	84,1	*						Tested At T + 36 hrs + 1 cycle
17	271,8	0,12		37,04	92,7	**	3619	3613	1,0			
18	273,3	0,17	0,19	36,17	90,5	***	3641	3636	0,9	3638	0,5	
19				37,81	94,6	*						Tested At T + 36 hrs + 2 Cycles
20	273,6	0,14		36,69	91,8	**	3626	3621	0,9			
21	270,3	0,16	0,15	37,38	93,6	***	3574	3571	0,5	3574	0,0	
22						*						Tested At T + 36 hrs + 2 Cycles
23	273,1	0,14		40,83		**	3614	3606	1,4			
24	270,5	0,18	0,21	36,26		***	3619	3614	0,9	3619	0,0	
Mean 1-24	272,0						3611					

* TESTED HOT

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE A.II.29

SPECIMEN SERIES : CMX

TEMPERATURE : 70°C

TREATMENT : SATURATED DURING HEATING

Spec. No.	PULSE VELOCITY				DYNAMIC YOUNG'S MODULUS				POISSON'S RATIO			
	* m/sec	** and *** m/sec	R.R %		* GPa	** and *** GPa	R.R %		*	** and ***	R.R %	
1	3928				26,83				0,289			
2	4011				26,81				0,305			
3	3969				16,68				0,301			
Mean of 1,2,3	3969				26,77				0,298			
4												
5	3969	3948	99,0	**	26,93	25,98	94,5	**	0,300	0,305	104,8	**
6	3990	3990	100,1	***	26,83	27,03	98,3	***	0,302	0,310	106,5	***
7												
8	4011	3888	97,5	**	27,31	25,76	93,7	**	0,301	0,299	102,7	**
9	3928	3928	98,5	***	26,65	25,82	93,9	***	0,287	0,299	102,7	***
10												
11	3948	3868	97,0	**	27,03	25,36	92,2	**	0,365	0,299	102,7	**
12	3990	3969	99,5	***	26,99	26,13	95,0	***	0,300	0,308	105,8	***
13												
14	3969	3928	98,5	**	27,03	25,34	92,1	**	0,297	0,312	107,2	**
15	3969	3868	97,0	***	27,18	26,15	95,1	***	0,298	0,294	101,0	***
16												
17	3969	3888	97,5	**	27,16	25,06	91,1	**	0,296	0,309	106,2	**
18	3969	3888	97,5	***	26,79	25,63	93,2	***	0,301	0,302	103,8	***
19												
20	3948	3848	96,5	**	26,37	24,73	89,9	**	0,301	0,305	104,8	**
21	3969	3868	97,0	***	26,76	25,43	92,5	***	0,298	0,298	102,4	***
22												
23	4011	3888		**	26,00	23,87		**	0,316	0,322		**
24	3969	3908		***	26,61	25,77		***	0,365	0,305		***
Mean of 1-24	3972				26,83				0,309			

* TESTED BEFORE HEATING

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE A.II.29 (contd.)

SPECIMEN SERIES : CMX

TEMPERATURE : 100°C

TREATMENT : SATURATED DURING HEATING

INITIAL WATER CONTENT = 592 g = W_t

VIZ. W_c = 304 g = 51,3%; W_n = 158 g = 26,7%; W_g = 130 g = 22,0%

Spec. No.	DEFORMATION			COMPRESSIVE STRENGTH			WATER LOSS					HEAT TREATMENT
	Initial length mm	Strain ** mm/m	Strain *** mm/m	MPa	R.R %		Mass before heat A(g)	Mass after heat B(g)	$\frac{A-B}{W_t}$ %	Mass after wett. C(g)	$\frac{A-C}{W_t}$ %	
1	272,3			38,50			3624					No Heating.
2	271,0			38,33			3633					Tested at
3	269,5			37,21			3536					Room Temp.
Mean 1,2,3	270,9			38,01			3598					
4				27,22	68,1	*						Tested Imm. Max. Temp. Attained (Time T)
5	272,3	0,16		31,87	79,8	**	3610	3604	1,0			
6	271,0	0,18	0,18	33,42	83,7	***	3638	3633	0,8	3636	0,3	
7				25,84	64,7	*						Tested At T + 12 hrs
8	272,3	0,19		29,18	73,3	**	3577	3571	1,0			
9	271,3	0,19	0,18	31,87	79,8	***	3619	3616	0,5	3619	0,0	
10				29,37	73,5	*						Tested At T + 24 hrs
11	271,0	0,20		33,42	83,7	**	3596	3593	0,5			
12	270,0	0,20	0,20	34,54	86,5	***	3549	3540	1,5	3551	-0,3	
13				33,25	83,2	*						Tested At T + 36 hrs
14	271,0	0,24		35,05	87,7	**	3570	3565	0,8			
15	270,8	0,23	0,22	30,32	75,9	***	3629	3625	0,7	3628	0,2	
16				32,38	81,1	*						Tested At T + 36 hrs + 1 cycle
17	271,8	0,26		34,97	87,5	**	3640	3635	0,8			
18	272,5	0,25	0,23	32,73	81,9	***	3648	3648	0,3	3650	-0,3	
19				34,37	86,0	*						Tested At T + 36 hrs + 2 Cycles
20	272,0	0,25		34,28	85,8	**	3586	3584	0,3			
21	274,1	0,27	0,23	34,97	87,5	***	3679	3677	0,3	3680	-0,2	
22						*						Tested At T + 36 hrs + 2 Cycles
23	270,8	0,27		34,97		**	3588	3583	0,8			
24	271,3	0,30	0,28	34,88		***	3622	3620	0,3	3621	+0,2	
Mean 1-24	271,5						3613					

* TESTED HOT

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE A.II.30

SPECIMEN SERIES : CMX

TEMPERATURE : 100°C

TREATMENT : SATURATED DURING HEATING

Spec. No.	PULSE VELOCITY				DYNAMIC YOUNG'S MODULUS				POISSON'S RATIO			
	* m/sec	** and *** m/sec	R.R %		* GPa	** and *** GPa	R.R %		*	** and ***	R.R %	
1	3948				26,40				0,302			
2	3969				26,43				0,308			
3	4011				26,40				0,308			
Mean of 1,2,3	3975				26,41				0,306			
4												
5	3948	3681	92,3	**	26,38	22,53	81,9	**	0,301	0,306	105,2	**
6	3969	3699	92,8	***	26,80	24,25	88,2	***	0,303	0,288	99,0	***
7												
8	3888	3611	90,6	**	25,89	21,57	78,4	**	0,293	0,305	104,8	**
9	3948	3646	91,4	***	26,52	23,30	84,7	***	0,301	0,290	99,7	***
10												
11	3969	3577	89,7	**	25,89	20,90	76,0	**	0,311	0,313	107,6	**
12	3969	3611	90,6	***	25,83	22,32	81,2	***	0,309	0,294	101,0	***
13												
14	3948	3611	90,6	**	25,67	21,28	77,4	**	0,308	0,311	106,9	**
15	3990	3663	91,9	***	25,88	23,08	83,9	***	0,318	0,299	102,7	***
16												
17	3948	3629	91,0	**	27,06	21,85	79,5	**	0,295	0,311	106,9	**
18	3969	3663	91,9	***	26,77	22,76	82,8	***	0,303	0,304	104,5	***
19												
20	3948	3594	90,1	**	25,69	21,44	78,0	**	0,308	0,305	104,8	**
21	3990	3681	92,3	***	26,80	23,47	85,3	***	0,307	0,297	102,1	***
22												
23	3969	3629		**	26,24	22,79		**	0,306	0,292		**
24	4011	3699		***	27,04	24,03		***	0,306	0,290		***
Mean of 1-24	3962				26,32				0,305			

* TESTED BEFORE HEATING

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE A.II.30 (contd.)

SPECIMEN SERIES : CMX

TEMPERATURE : 70°C

TREATMENT : DRYING DURING HEATING

INITIAL WATER CONTENT = 592 g = W_t

VIZ. W_c = 304 g = 51,3%; W_n = 158 g = 26,9%; W_g = 130 g = 22,0%

Spec. No.	DEFORMATION			COMPRESSIVE STRENGTH		WATER LOSS					HEAT TREATMENT
	Initial length mm	Strain ** mm/m	Strain *** mm/m	MPa	R.R %	Mass before heat A(g)	Mass after heat B(g)	$\frac{A-B}{W_t}$ %	Mass after wett. C(g)	$\frac{A-C}{W_t}$ %	
1	273,3			38,32		3630					No Heating.
2	271,4			38,58		3609					Tested at
3	272,2			38,44		3616					Room Temp.
Mean 1,2,3	272,3			38,41		3618					
4				37,90	94,9*						Tested Imm.
5	272,5	-0,23		44,44	111,2**	3635	3541	15,9			Max. Temp.
6	272,8	-0,25	-0,02	39,02	97,7***	3591	3492	16,7	3563	4,7	Attained (Time T)
7				39,36	98,5*						Tested At
8	272,5	-0,29		42,63	106,7**	3651	3503	25,0			T + 12 hrs
9	273,3	-0,25	-0,04	37,04	92,7***	3642	3480	27,4	3622	3,4	
10				38,24	95,7*						Tested At
11	272,0	-0,31		43,93	110,0**	3606	3419	31,6			T + 24 hrs
12	271,5	-0,33	-0,07	36,95	92,5***	3507	3327	32,1	3485	3,7	
13				40,31	100,9*						Tested At
14	273,1	-0,38		40,48	101,3**	3630	3415	36,3			T + 36 hrs
15	272,8	-0,35	-0,07	34,37	86,0***	3609	3408	34,0	3590	3,2	
16				38,07	95,3*						Tested At
17	273,6	-0,50		42,63	106,7**	3616	3380	39,9			T + 36 hrs
18	273,6	-0,42	-0,08	36,09	90,3***	3654	3409	41,4	3630	4,1	+ 1 cycle
19				40,31	100,9*						Tested At
20	273,8	-0,54		42,65	106,7**	3614	3393	37,3			T + 36 hrs
21	272,3	-0,47	0,09	38,07	95,3***	3526	3295	39,0	3505	3,4	+ 2 Cycles
22					*						Tested At
23	272,8	-0,52		40,14	**	3540	3291	42,1			T + 36 hrs
24	273,1	-0,50	-0,13	35,74	***	3591	3351	40,5	3372	3,2	+ 2 Cycles
Mean 1-24	272,8					3601					

* TESTED HOT

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE A.II.31

SPECIMEN SERIES : CMX

TEMPERATURE : 70°C

TREATMENT : DRYING DURING HEATING

Spec. No.	PULSE VELOCITY				DYNAMIC YOUNG'S MODULUS				POISSON'S RATIO			
	* m/sec	** and *** m/sec	R.R %		* GPa	** and *** GPa	R.R %		*	** and ***	R.R %	
1	4011				29,39				0,271			
2	3990				28,67				0,278			
3	4032				28,46				0,289			
Mean of 1,2,3	4011				28,84				0,279			
4												
5	3990	3848	96,5	**	29,43	27,85	101,3	**	0,267	0,245	84,2	**
6	3969	3888	97,5	***	27,23	27,96	101,7	***	0,270	0,257	88,3	***
7												
8	4075	3717	93,2	**	30,13	26,70	97,1	**	0,278	0,222	76,3	**
9	4011	3888	97,5	***	26,54	27,89	101,4	***	0,265	0,265	91,1	***
10												
11	4032	3646	91,4	**	28,95	25,44	92,5	**	0,281	0,214	73,5	**
12	4011	3829	96,0	***	24,71	26,22	95,3	***	0,277	0,265	91,1	***
13												
14	3990	3594	90,1	**	29,80	26,17	95,2	**	0,260	0,159	54,6	**
15	3969	3810	95,6	***	24,79	27,05	98,4	***	0,271	0,257	88,3	***
16												
17	3990	3561	89,3	**	28,82	24,34	885,	**	0,273	0,198	68,0	**
18	3908	3681	92,3	***	24,31	26,00	94,5	***	0,259	0,246	84,5	***
19												
20	3990	3594	90,1	**	29,76	25,25	91,8	**	0,257	0,185	63,6	**
21	4011	3810	95,6	***	24,23	25,86	94,0	***	0,273	0,268	92,1	***
22												
23	3948	3544		**	27,86	23,63		**	0,270	0,195		**
24	4011	3810		***	26,51	26,51		***	0,270	0,264		***
Mean of 1-24	3993				29,04				0,269			

* TESTED BEFORE HEATING

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE A.II.31 (contd.)

SPECIMEN SERIES : CMX

TEMPERATURE : 100°C

TREATMENT : DRYING DURING HEATING

INITIAL WATER CONTENT = 592 g = W_t

VIZ. W_c = 304 g = 51,3%; W_n = 158 g = 26,7%; W_g = 130 g = 22,0%

Spec. No.	DEFORMATION			COMPRESSIVE STRENGTH			WATER LOSS					HEAT TREATMENT
	Initial length mm	Strain ** mm/m	Strain *** mm/m	MPa	R.R %		Mass before heat A(g)	Mass after heat B(g)	$\frac{A-B}{W_t}$ %	Mass after wett. C(g)	$\frac{A-C}{W_t}$ %	
1	271,6			42,46			3599					No Heating.
2	272,2			42,72			3578					Tested at
3	273,4			42,20			3607					Room Temp.
Mean 1,2,3	272,4			42,46			3595					
4				31,87	79,8	*						Tested Imm. Max. Temp. Attained (Time T)
5	271,5	-0,32		38,59	96,6	**	3574	3395	30,2			
6	271,3	-0,29	-0,01	36,17	90,5	***	3589	3416	29,2	3566	3,9	
7				35,31	88,4	*						Tested At T + 12 hrs
8	271,3	-0,40		36,53	91,4	**	3590	3329	44,1			
9	272,3	-0,42	-0,13	34,28	85,8	***	3578	3270	52,0	3551	4,6	
10				37,47	93,8	*						Tested At T + 24 hrs
11	271,8	-0,51		41,26	103,3	**	3592	3269	54,6			
12	271,5	-0,56	-0,22	31,87	79,8	***	3595	3273	54,4	3566	4,9	
13				40,14	100,5	*						Tested At T + 36 hrs
14	270,5	-0,58		39,96	100,0	**	3599	3245	59,8			
15	271,5	-0,57	-0,22	31,95	80,0	***	3617	3267	59,1	3585	5,4	
16				39,10	97,9	*						Tested At T + 36 hrs + 1 cycle
17	272,8	-0,63		41,26	103,3	**	3601	3230	62,7			
18	273,1	-0,61	-0,24	33,25	83,2	***	3607	3249	60,5	3575	5,4	
19				37,72	94,4	*						Tested At T + 36 hrs + 2 Cycles
20	272,0	-0,65		40,48	101,3	**	3601	3243	60,5			
21	271,5	-0,65	-0,27	31,70	79,3	***	3580	3214	61,8	3549	5,9	
22						*						Tested At T + 36 hrs + 2 Cycles
23	270,3	-0,77		42,55		**	3549	3166	64,7			
24	271,8	-0,68	-0,27	33,33		***	3600	3233	62,0	3563	6,3	
Mean 1-24	271,8						3591					

* TESTED HOT

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE A.II.32

SPECIMEN SERIES : CMX

TEMPERATURE : 100°C

TREATMENT : DRYING DURING HEATING

Spec. No.	PULSE VELOCITY				DYNAMIC YOUNG'S MODULUS				POISSON'S RATIO			
	* m/sec	** and *** m/sec	R.R %		* GPa	** and *** GPa	R.R %		*	** and ***	R.R %	
1	4075				29,79				0,211			
2	4053				29,94				0,267			
3	4011				28,41				0,283			
Mean of 1,2,3	4047				29,38				0,254			
4												
5	4053	3594	90,1	**	29,16	24,16	87,8	**	0,280	0,226	77,7	**
6	3990	3681	92,3	***	29,01	26,13	95,0	***	0,270	0,238	81,8	***
7												
8	3990	3472	87,3	**	30,22	22,71	82,6	**	0,250	0,210	72,2	**
9	3990	3544	88,9	***	29,50	23,54	85,6	***	0,259	0,249	85,6	***
10												
11	4032	3448	86,5	**	29,76	21,86	79,5	**	0,268	0,211	72,5	**
12	4011	3544	88,9	***	29,47	23,23	84,5	***	0,268	0,260	89,3	***
13												
14	4011	3417	85,7	**	29,68	21,85	79,5	**	0,267	0,195	67,0	**
15	3948	3464	86,9	***	29,94	23,10	84,0	***	0,247	0,241	82,8	***
16												
17	3990	3372	84,6	**	29,18	21,56	78,4	**	0,267	0,171	58,8	**
18	3990	3464	86,9	***	29,53	22,87	83,2	***	0,261	0,242	83,2	***
19												
20	4075	3479	87,3	**	29,66	22,33	81,2	**	0,279	0,201	69,1	**
21	3969	3417	85,7	***	29,63	22,24	80,9	***	0,253	0,241	82,8	***
22												
23	3969	3387		**	29,41	21,05		**	0,255	0,191		**
24	4097	3512		***	30,86	23,23		***	0,267	0,249		***
Mean of 1-24	4008				29,64				0,264			

* TESTED BEFORE HEATING

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE A.II.32 (contd.)

SPECIMEN SERIES : CMX

TEMPERATURE : 150°C

TREATMENT : DRYING DURING HEATING

INITIAL WATER CONTENT = 592 g = W_t

VIZ. W_c = 304 g = 51,3%

W_n = 158 g = 26,7%

W_g = 130 g = 22,0%

Spec. No.	DEFORMATION			COMPRESSIVE STRENGTH			WATER LOSS					HEAT TREATMENT
	Initial length mm	Strain ** mm/m	Strain *** mm/m	MPa	R.R %		Mass before heat A(g)	Mass after heat B(g)	$\frac{A-B}{W_t}$ %	Mass after wett. C(g)	$\frac{A-C}{W_t}$ %	
1	271,8			39,27			3550					No Heating.
2	271,8			34m28			3616					Tested at
3	273,6			37,03			3548					Room Temp.
Mean 1,2,3	272,4			36,86			3571					
4				37,55	94,0	*						Tested Imm.
5	271,0	-0,35		35,83	89,7	**	3559	3194	61,7			Max. Temp.
6	271,8	-0,35	0,06	28,60	71,6	***	3544	3199	58,3	3509	5,9	Attained (Time T)
7				40,65	101,8	*						Tested At
8	269,7	-0,56		38,41	96,1	**	3548	3150	67,2			T + 12 hrs
9	272,5	-0,58	0,09	28,94	72,4	***	3550	3152	67,2	3488	10,5	
10				34,80	87,1	*						Tested At
11	270,8	-0,63		35,83	89,7	**	3525	3117	68,9			T + 24 hrs
12	271,8	-0,58	0,07	29,46	73,7	***	3584	3186	67,2	3537	4,6	
13				40,65	101,8	*						Tested At
14	273,1	-0,70		35,31	88,4	**	3594	3194	67,6			T + 36 hrs
15	271,3	-0,63	0,08	26,61	66,6	***	3565	3155	69,3	3524	6,9	
16				39,79	99,6	*						Tested At
17	272,5	-0,67		43,58	109,1	**	3581	3169	69,6			T + 36 hrs
18	271,0	-0,65	0,07	29,11	72,9	***	3583	3180	68,1	3534	8,3	+ 1 cycle
19				37,12	92,9	*						Tested At
20	271,5	-0,62		42,38	106,1	**	3615	3199	70,3			T + 36 hrs
21	269,5	-0,62	0,09	28,77	72,0	***	3522	3132	67,4	3473	8,3	+ 2 Cycles
22						*						Tested At
23	270,0	-0,67		41,86		**	3576	3170	68,6			T + 36 hrs
24	270,8	-0,71	0,09	25,84		***	3544	3131	69,8	3483	10,3	+ 2 Cycles
Mean 1-24	271,3						3564					

* TESTED HOT

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE A.II.33

SPECIMEN SERIES : CMX

TEMPERATURE : 150°C

TREATMENT : DRYING DURING HEATING

Spec. No.	PULSE VELOCITY				DYNAMIC YOUNG'S MODULUS				POISSON'S RATIO			
	* m/sec	** and *** m/sec	R.R %		* GPa	** and *** GPa	R.R %		*	** and ***	R.R %	
1	4011				24,63				0,328			
2	3928				24,32				0,325			
3	4011				25,09				0,320			
Mean of 1,2,3	3983				24,68				0,324			
4												
5	3969	3270	82,0	**	24,17	18,41	66,9	**	0,329	0,240	82,5	**
6	4011	3464	86,9	***	24,44	21,51	78,2	***	0,329	0,267	91,8	***
7												
8	4011	3229	81,0	**	2491	18,91	68,8	**	0,327	0,199	68,4	**
9	3969	3243	81,3	***	24,69	21,03	76,5	***	0,320	0,194	66,7	***
10												
11	3908	3085	77,4	**	23,76	18,00	65,5	**	0,322	0,140	48,1	**
12	4011	3342	83,8	***	24,86	21,00	76,4	***	0,328	0,243	83,5	***
13												
14	4075	3229	81,0	**	25,21	18,94	68,9	**	0,332	0,198	68,0	**
15	3990	3357	84,2	***	24,08	20,59	74,9	***	0,332	0,260	89,3	***
16												
17	4011	3149	79,0	**	22,79	19,47	70,8	**	0,349	0,091	32,3	**
18	4011	3372	84,6	***	23,04	21,66	78,8	***	0,348	0,240	82,5	***
19												
20	3948	3175	79,6	**	23,13	18,98	69,0	**	0,341	0,173	59,5	**
21	4011	3357	84,2	***	23,71	20,83	75,7	***	0,338	0,292	100,3	***
22												
23	4032	3243		**	23,89	18,93		**	0,342	0,208		**
24	3928	3243		***	25,59	20,17		***	0,303	0,228		***
Mean of 1-24	3992				24,16				0,331			

* TESTED BEFORE HEATING

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE A.II.33 (contd.)

SPECIMEN SERIES : CMX

TEMPERATURE : 250°C

TREATMENT : DRYING DURING HEATING

INITIAL WATER CONTENT = 592 g = W_t

VIZ. W_c = 304 g = 51,3%; W_n = 158 g = 26,7%; W_g = 130 g = 22,0%

Spec. No.	DEFORMATION			COMPRESSIVE STRENGTH			WATER LOSS					HEAT TREATMENT
	Initial length mm	Strain ** mm/m	Strain *** mm/m	MPa	R.R %		Mass before heat A(g)	Mass after heat B(g)	$\frac{A-B}{W_t}$ %	Mass after wett. C(g)	$\frac{A-C}{W_t}$ %	
1	270,3			41,00			3539					No Heating. Tested at Room Temp.
2	272,9			39,79			3501					
3	271,6			40,65			3632					
Mean 1,2,3	271,6			40,48			3557					
4				34,80	87,1	*						Tested Imm. Max. Temp. Attained (Time T)
5	271,8	-0,25		37,90	94,9	**	3599	3178	71,1			
6	270,5	-0,29	0,61	30,15	75,5	***	3520	3120	67,6	3502	3,0	
7				42,72	106,9	*						Tested At T + 12 hrs
8	269,7	-0,46		34,71	86,9	**	3563	3150	69,8			
9	269,0	-0,45	0,73	25,84	64,7	***	3575	3151	71,6	3552	3,9	
10				41,17	103,1	*						Tested At T + 24 hrs
11	269,0	-0,40		31,70	79,3	**	3501	3080	71,1			
12	271,8	-0,47	0,53	27,90	69,8	***	3582	3167	70,1	3567	4,2	
13				40,14	100,5	*						Tested At T + 36 hrs
14	272,8	-0,46		34,45	86,2	**	3566	3145	71,1			
15	270,0	-0,53	0,56	27,22	68,1	***	3556	3138	70,6	3533	3,9	
16				41,34	103,5	*						Tested At T + 36 hrs + 1 cycle
17	271,5	-0,47		33,25	83,2	**	3539	3124	70,1			
18	273,6	-0,49	0,66	27,04	67,7	***	3632	3203	72,5	3613	3,2	
19				42,38	106,1	*						Tested At T + 36 hrs + 2 Cycles
20	270,0	-0,60		31,70	79,3	**	3555	3235	70,9			
21	270,0	-0,63	0,46	26,70	66,8	***	3552	3138	69,9	3538	2,4	
22						*						Tested At T + 36 hrs + 2 Cycles
23	268,2	-0,63		28,77		**	3486	3066	70,9			
24	269,7	-0,61	0,42	27,04		***	3551	3122	72,5	3521	5,1	
Mean 1-24	270,5						3556					

* TESTED HOT

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE A.II.34

SPECIMEN SERIES : CMX

TEMPERATURE : 250°C

TREATMENT : DRYING DURING HEATING

Spec. No.	PULSE VELOCITY				DYNAMIC YOUNG'S MODULUS				POISSON'S RATIO			
	* m/sec	** and *** m/sec	R.R %		* GPa	** and *** GPa	R.R %		*	** and ***	R.R %	
1	3969				29,25				0,256			
2	3928				29,58				0,226			
3	3969				29,88				0,236			
Mean of 1,2,3	3956				29,57				0,246			
4												
5	3928	2751	69,0	**	29,71	14,42	52,4	**	0,243	0,151	51,9	**
6	3990	3464	86,9	***	29,29	19,92	72,4	***	0,258	0,299	102,7	***
7												
8	4011	2875	72,1	**	29,38	14,58	53,0	**	0,269	0,219	75,3	**
9	3990	3448	86,5	***	29,31	18,79	68,3	***	0,268	0,322	110,7	***
10												
11	3948	2674	67,1	**	28,70	12,94	47,1	**	0,257	0,183	62,9	**
12	3928	3464	86,9	***	28,74	19,34	70,3	***	0,258	0,314	107,9	***
13												
14	3948	2791	70,0	**	29,25	13,26	48,2	**	0,250	0,234	80,4	**
15	3990	3464	86,9	***	29,53	19,69	71,6	***	0,261	0,307	105,5	***
16												
17	3908	2646	66,4	**	29,29	12,37	45,0	**	0,236	0,207	71,1	**
18	3928	3479	87,3	***	29,88	19,57	71,2	***	0,241	0,315	108,2	***
19												
20	3928	2731	68,5	**	29,57	13,11	47,7	**	0,242	0,399	137,1	**
21	3948	3448	86,5	***	28,84	19,06	69,3	***	0,260	0,315	108,2	***
22												
23	3948	2781		**	28,12	12,67		**	0,267	0,251		**
24	3969	3417		***	29,55	18,56		***	0,254	0,317		***
Mean of 1-24	3955				29,24				0,255			

* TESTED BEFORE HEATING

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE A.II.34 (contd.)

SPECIMEN SERIES : CMX

TEMPERATURE : 400°C

TREATMENT : DRYING DURING HEATING

INITIAL WATER CONTENT = 592 g = W_t

VIZ. W_c = 304 g = 51,3%

W_n = 158 g = 26,7%

W_g = 130 g = 22,0%

Spec. No.	DEFORMATION			COMPRESSIVE STRENGTH			WATER LOSS					HEAT TREATMENT
	Initial length mm	Strain ** mm/m	Strain *** mm/m	MPa	R.R %		Mass before heat A(g)	Mass after heat B(g)	$\frac{A-B}{W_t}$ %	Mass after wett. C(g)	$\frac{A-C}{W_t}$ %	
1	271,9			43,07			3599					No Heating.
2	272,4			41,00			3563					Tested at
3	270,8			42,73			3559					Room Temp.
Mean 1,2,3	271,7			42,26			3584					
4				35,14	88,0	*						Tested Imm. Max. Temp. Attained (Time T)
5	272,0	1,08		27,99	70,1	**	3628	3162	78,7			
6	269,2	0,94	2,42	25,49	63,8	***	3563	3109	76,7	3533	5,1	
7				36,17	90,5	*						Tested At T + 12 hrs
8	270,3	0,84		27,56	69,0	**	3629	3160	79,2			
9	271,0	1,99	3,40	27,56	69,0	***	3588	3116	79,7	3561	4,6	
10				36,43	91,2	*						Tested At T + 24 hrs
11	270,0	1,35		26,61	66,6	**	3565	3098	78,9			
12	270,5	1,13	2,64	27,91	69,9	***	3588	3126	78,0	3561	4,6	
13				34,80	87,1	*						Tested At T + 36 hrs
14	270,8	2,33		26,01	65,1	**	3599	3119	81,1			
15	270,3	1,17	2,62	29,89	74,8	***	3526	3063	78,2	3505	3,5	
16				35,74	89,5	*						Tested At T + 36 hrs + 1 cycle
17	270,3	2,17		25,41	63,6	**	3519	3044	80,2			
18	271,5	1,78	2,73	26,36	66,0	***	3579	3095	81,8	3565	2,4	
19				33,16	83,0	*						Tested At T + 36 hrs + 2 Cycles
20	270,8	1,24		29,54	73,9	**	3567	3095	79,7			
21	270,8	1,02	2,57	26,53	66,4	***	3572	3099	79,9	3548	4,1	
22						*						Tested At T + 36 hrs + 2 Cycles
23	270,0	1,47		29,71		**	3562	3080	81,4			
24	271,0	1,29	2,64	28,94		***	3552	3081	79,6	3533	3,2	
Mean 1-24	270,5						3574					

* TESTED HOT

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE A.II.35

SPECIMEN SERIES : CMX

TEMPERATURE : 400°C

TREATMENT : DRYING DURING HEATING

Spec. No.	PULSE VELOCITY				DYNAMIC YOUNG'S MODULUS				POISSON'S RATIO			
	* m/sec	** and *** m/sec	R.R %		* GPa	** and *** GPa	R.R %		*	** and ***	R.R %	
1	4053				27,24				0,307			
2	4011				27,92				0,286			
3	4032				26,85				0,306			
Mean of 1,2,3	4032				27,34				0,300			
4												
5	3969	2059	51,6	**	27,52	7,59	27,6	**	0,291	0,205	70,4	**
6	4053	3561	89,3	***	27,42	19,76	71,9	***	0,305	0,324	111,3	***
7												
8	4032	21	53,8	**	28,04	7,71	28,0	**	0,299	0,251	86,3	**
9	4075	3663	91,9	***	27,63	22,15	80,5	***	0,306	0,306	105,2	***
10												
11	4053	2043	51,2	**	27,01	6,87	25,0	**	0,309	0,250	85,9	**
12	4053	3646	91,4	***	27,57	21,32	77,5	***	0,304	0,316	108,6	***
13												
14	3990	1905	47,8	**	27,25	4,15	15,1	**	0,298	0,366	125,8	**
15	4075	3699	92,8	***	26,99	22,25	80,9	***	0,309	0,307	105,5	***
16												
17	4011	1832	45,9	**	26,60	4,94	18,0	**	0,303	0,292	100,3	**
18	3928	3592	90,1	***	26,84	20,22	73,5	***	0,288	0,322	110,7	***
19												
20	4053	1934	48,5	**	27,52	5,71	10,8	**	0,302	0,284	97,6	**
21	4011	3592	90,1	***	26,63	20,85	75,8	***	0,307	0,312	107,2	***
22												
23	4032	1859		**	27,32	5,25		**	0,302	0,285		**
24	4053	3681		***	27,01			***	0,307			***
Mean of 1-24	4028				27,24				0,302			

* TESTED BEFORE HEATING

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE A.II.35 (contd.)

SPECIMEN SERIES : CMY

TEMPERATURE : 70°C

TREATMENT : SATURATED DURING HEATING

INITIAL WATER CONTENT = 553 g = W_t

VIZ. W_c = 284 g = 51,3%
W_n = 147 g = 26,6%
W_g = 122 g = 22,1%

Spec. No.	DEFORMATION			COMPRESSIVE STRENGTH			WATER LOSS					HEAT TREATMENT
	Initial length mm	Strain ** mm/m	Strain *** mm/m	MPa	R.R %		Mass before heat A(g)	Mass after heat B(g)	$\frac{A-B}{W_t}$ %	Mass after wett. C(g)	$\frac{A-C}{W_t}$ %	
1	272,0			39,19			3663					No Heating.
2	273,1			41,77			3702					Tested at
3	272,8			41,00			3637					Room Temp.
Mean 1,2,3	272,6			40,65			3667					
4				33,76	88,4	*						Tested Imm.
5	271,0	0,10		40,57	106,2	**	3626	3629	-0,5			Max. Temp.
6	271,5	0,10	0,09	43,07	112,7	***	3613	3615	-0,4	3621	-1,5	Attained (Time T)
7				32,73	85,7	*						Tested At
8	272,3	0,12		38,41	100,5	**	3704	3702	+0,4			T + 12 hrs
9	271,3	0,15	0,15	39,02	102,1	***	3641	3638	+0,5	3643	-0,4	
10				35,40	92,7	*						Tested At
11	272,3	0,19		36,69	96,0	**	3613	3611	+0,4			T + 24 hrs
12	271,8	0,20	0,18	38,93	101,9	***	3685	3681	0,7	3685	0,0	
13				35,66	93,4	*						Tested At
14	271,8	0,21		34,54	90,4	**	3686	3682	+0,7			T + 36 hrs
15	271,8	0,18	0,17	39,28	102,8	***	3659	3655	+0,7	3661	-0,4	
16				37,81	99,0	*						Tested At
17	270,0	0,22		36,26	94,9	**	3632	3628	+0,7			T + 36 hrs
18	270,0	0,20	0,21	37,90	99,2	***	3619	3613	+1,1	3620	-0,2	+ 1 cycle
19				37,81	99,0	*						Tested At
20	273,1	0,21		36,26	94,9	**	3671	3669	0,4			T + 36 hrs
21	273,1	0,20	0,21	37,90	99,2	***	3649	3645	0,7	3651	-0,4	+ 2 Cycles
22						*						Tested At
23	270,8	0,18		38,93		**	3600	3590	-1,8			T + 36 hrs
24	271,3	-	-	-		***	3640	-	-	-	-	+ 2 Cycles
Mean 1-24	271,5						3645					

* TESTED HOT

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE A.II.36

SPECIMEN SERIES : CMY

TEMPERATURE : 70°C

TREATMENT : SATURATED DURING HEATING

Spec. No.	PULSE VELOCITY				DYNAMIC YOUNG'S MODULUS				POISSON'S RATIO			
	* m/sec	** and *** m/sec	R.R %		* GPa	** and *** GPa	R.R %		*	** and ***	R.R %	
1	4032				30,15				0,270			
2	4032				27,83				0,305			
3	4071				28,55				0,296			
Mean of 1,2,3	4025				28,84				0,290			
4												
5	4011	3990	99,9	**	27,83	26,40	94,3	**	0,296	0,311	111,1	**
6	4032	3990	99,9	***	27,52	27,84	97,6	***	0,302	0,291	103,9	***
7												
8	4075	3908	97,8	**	28,30	26,88	90,2	**	0,307	0,300	107,1	**
9	4032	3969	99,3	***	27,62	27,03	92,8	***	0,304	0,300	107,1	***
10												
11	4011	3848	96,3	**	28,36	25,89	89,7	**	0,286	0,289	103,2	**
12	4032	3928	98,3	***	27,49	27,39	95,2	***	0,309	0,291	103,9	***
13												
14	4032	3908	97,8	**	27,58	25,07	92,2	**	0,308	0,318	113,6	**
15	4053	3948	98,8	***	27,81	25,73	92,9	***	0,306	0,314	112,1	***
16												
17	4075	3888	97,3	**	27,51	25,16	90,0	**	0,313	0,311	111,1	**
18	4053	3969	99,3	***	28,65	26,91	90,7	***	0,294	0,301	107,5	***
19												
20	4075	3879	97,1	**	28,21	25,98	88,3	**	0,304	0,314	112,1	**
21	4032	3943	98,7	***	28,22	26,61	92,4	***	0,294	0,300	107,1	***
22												
23	4011	3848		**	26,66	25,44		**	0,309	0,295		**
24	4075			***	28,50			***	0,300			***
Mean of 1-24	4043				27,88				0,302			

* TESTED BEFORE HEATING

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE A.II.36 (contd.)

SPECIMEN SERIES : CMY

TEMPERATURE : 100°C

TREATMENT : SATURATED DURING HEATING

INITIAL WATER CONTENT = 553 g = W_t

VIZ. W_c = 28,4 g = 51,3%
W_n = 147 g = 26,6%
W_g = 122 g = 22,1%

Spec. No.	DEFORMATION			COMPRESSIVE STRENGTH			WATER LOSS					HEAT TREATMENT
	Initial length mm	Strain ** mm/m	Strain *** mm/m	MPa	R.R %		Mass before heat A(g)	Mass after heat B(g)	$\frac{A-B}{W_t}$ %	Mass after wett. C(g)	$\frac{A-C}{W_t}$ %	
1	272,0			33,68			3550					No Heating. Tested at Room Temp.
2	270,8			36,52			3507					
3	270,8			36,52			3524					
Mean 1,2,3	271,2			35,57			3527					
4				25,41	66,5	*						Tested Imm. Max. Temp. Attained (Time T)
5	272,0	0,12		26,87	70,3	**	3503	3500	0,5			
6	271,5	0,12	0,13	31,35	82,1	***	3498	3495	0,5	3497	0,2	
7				24,37	63,8	*						Tested At T + 12 hrs
8	274,6	0,19		31,27	81,9	**	3554	3548	1,1			
9	270,3	0,17	0,16	30,75	80,5	***	3522	3520	0,4	3521	0,2	
10				29,46	77,1	*						Tested At T + 24 hrs
11	273,1	0,20		31,78	83,2	**	3624	3618	1,1			
12	273,1	0,18	0,19	30,40	79,6	***	3612	3607	0,9	3610	0,4	
13				31,52	82,5	*						Tested At T + 36 hrs
14	273,8	0,20		32,90	86,1	**	3564	3560	0,7			
15	273,3	0,20	0,18	32,64	85,4	***	3563	3531	0,9	3531	0,9	
16				31,87	83,4	*						Tested At T + 36 hrs + 1 cycle
17	271,8	0,20		34,80	91,1	**	3502	3500	0,4			
18	272,8	0,18	0,19	31,18	81,6	***	3542	3539	0,5	3540	0,4	
19				33,76	88,4	*						Tested At T + 36 hrs + 2 Cycles
20	270,3	0,19		33,33	87,3	**	3517	3513	0,7			
21	273,1	0,19	0,20	31,61	82,7	***	3600	3599	0,2	3599	0,2	
22						*						Tested At T + 36 hrs + 2 Cycles
23	272,5	0,20		36,00		**	3653	3555	1,4			
24	273,8	0,22	0,22	33,59		***	3621	3613	1,4	3621	0,0	
Mean 1-24	272,5						3554					

* TESTED HOT

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE A.II.37

SPECIMEN SERIES : CMY

TEMPERATURE : 100°C

TREATMENT : SATURATED DURING HEATING

Spec. No.	PULSE VELOCITY				DYNAMIC YOUNG'S MODULUS				POISSON'S RATIO			
	* m/sec	** and *** m/sec	R.R %		* GPa	** and *** GPa	R.R %		*	** and ***	R.R %	
1	3990				26,00				0,308			
2	3990				25,96				0,306			
3	3990				26,09				0,305			
Mean of 1,2,3	3990				26,02				0,306			
4												
5	3948	3681	92,1	**	26,66	22,67	79,8	**	0,286	0,294	105,0	**
6	3990	3848	96,3	***	26,31	24,10	84,9	***	0,299	0,304	108,6	***
7												
8	4011	3681	92,1	**	26,95	22,12	77,9	**	0,296	0,304	108,6	**
9	3969	3717	93,0	***	26,02	22,77	80,2	***	0,303	0,304	108,6	***
10												
11	3969	3629	90,8	**	27,05	22,69	79,9	**	0,241	0,294	105,0	**
12	3908	3646	91,3	***	25,98	21,15	74,5	***	0,298	0,320	114,3	***
13												
14	3928	3629	90,8	**	26,44	21,35	75,2	**	0,289	0,309	110,4	**
15	3990	3717	93,0	***	26,61	22,31	78,6	***	0,296	0,308	110,0	***
16												
17	4011	3699	92,6	**	26,89	22,58	79,5	**	0,295	0,299	106,8	**
18	3948	3717	93,0	***	25,77	22,11	77,9	***	0,302	0,312	111,4	***
19												
20	4053	3699	92,6	**	26,50	22,53	79,3	**	0,312	0,303	108,2	**
21	3948	3699	92,6	***	26,38	22,72	80,0	***	0,299	0,227	81,1	***
22												
23	4032	3754		**	27,24	23,18		**	0,299	0,305		**
24	3928	3735		***	26,61	23,22		***	0,293	0,306		***
Mean of 1-24	3974				26,53				0,293			

* TESTED BEFORE HEATING

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE A.II.37 (contd.)

SPECIMEN SERIES : CMY

TEMPERATURE : 70°C

TREATMENT : DRYING DURING HEATING

INITIAL WATER CONTENT = 553 g = W_t

VIZ. W_c = 284 g; W_n = 147 g; W_g = 122 g

Spec. No.	DEFORMATION			COMPRESSIVE STRENGTH		WATER LOSS					HEAT TREATMENT
	Initial length mm	Strain ** mm/m	Strain *** mm/m	MPa	R.R %	Mass before heat A(g)	Mass after heat B(g)	$\frac{A-B}{W_t}$ %	Mass after wett. C(g)	$\frac{A-C}{W_t}$ %	
1	271,1			36,69		3599					No Heating. Tested at Room Temp.
2	270,6			39,79		3574					
3	272,5			38,93		3648					
Mean 1,2,3	271,4			38,53		3607					
4				32,90	86,1 *						Tested Imm. Max. Temp. Attained (Time T)
5	269,7	-0,26		40,14	105,1 **	3541	3437	18,8			
6	270,8	-0,30	0,07	41,17	107,8 ***	3635	3532	18,6	3607	5,1	
7				33,94	88,8 *						Tested At T + 12 hrs
8	270,5	-0,29		37,21	97,4 **	3621	3477	26,0			
9	272,3	-0,26	0,04	35,14	92,0 ***	3598	3453	26,2	35,71	4,9	
10				36,17	94,7 *						Tested At T + 24 hrs
11	272,5	-0,33		42,38	110,9 **	3615	3445	30,7			
12	271,8	-0,32	0,05	37,90	99,2 ***	3613	3446	30,2	3592	3,8	
13				35,31	92,4 *						Tested At T + 36 hrs
14	270,0	-0,34		46,34	121,3 **	3531	3354	32,0			
15	271,0	-0,36	0,08	36,00	94,2 ***	3604	3426	32,2	3573	5,6	
16				36,33	95,1 *						Tested At T + 36 hrs + 1 cycle
17	270,8	-0,37		43,75	114,5 **	3593	3392	36,3			
18	270,8	-0,33	0,08	35,66	93,4 ***	3626	3434	34,7	3597	5,2	
19				41,17	107,8 *						Tested At T + 36 hrs + 2 Cycles
20	270,3	-0,38		43,06	112,7 **	3540	3338	36,5			
21	270,0	-0,36	0,08	37,90	99,2 ***	3579	3384	35,3	3553	4,7	
22					*						Tested At T + 36 hrs + 2 Cycles
23	271,3	-0,39		42,03	**	3618	3428	34,4			
24	272,0	-0,37	0,09	3807	***	3594	3397	35,6	3558	6,5	
Mean 1-24	271,0					3593					

* TESTED HOT

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE A.II.38

SPECIMEN SERIES : CMY

TEMPERATURE : 100°C

TREATMENT : DRYING DURING HEATING

INITIAL WATER CONTENT = 553 g = W_t

VIZ. W_c = 284 g = 51,3%
W_n = 147 g = 26,6%
W_g = 122 g = 22,1%

Spec. No.	DEFORMATION			COMPRESSIVE STRENGTH			WATER LOSS					HEAT TREATMENT
	Initial length mm	Strain ** mm/m	Strain *** mm/m	MPa	R.R %		Mass before heat A(g)	Mass after heat B(g)	$\frac{A-B}{W_t}$ %	Mass after wett. C(g)	$\frac{A-C}{W_t}$ %	
1	272,6			41,34			3654					No Heating. Tested at Room Temp.
2	270,9			37,64			3587					
3	273,7			40,66			3668					
Mean 1,2,3	272,4			39,88			3636					
4				31,18	81,6	*						Tested Imm. Max. Temp. Attained (Time T)
5	271,3	-0,19		36,52	95,6	**	3558	3376	32,9			
6	273,3	-0,18	0,0	32,38	84,8	***	3663	3485	32,2	3646	3,1	
7				32,56	85,2	*						Tested At T + 12 hrs
8	272,8	-0,35		35,83	93,8	**	3673	3409	47,7			
9	272,0	-0,37	-0,13	32,38	84,8	***	3610	3319	55,9	3554	4,7	
10				34,19	89,5	*						Tested At T + 24 hrs
11	271,5	-0,44		39,79	104,2	**	3581	3266	57,0			
12	270,8	-0,48	-0,20	30,32	79,4	***	3606	3288	57,5	3580	4,7	
13				37,04	97,0	*						Tested At T + 36 hrs
14	272,5	-0,60		39,45	103,3	**	3597	3274	58,4			
15	272,3	-0,50	-0,20	30,15	78,9	***	3589	3258	59,9	3568	3,8	
16				37,72	98,7	*						Tested At T + 36 hrs + 1 cycle
17	271,3	-0,65		38,76	101,5	**	3649	3302	62,7			
18	272,0	-0,54	-0,20	33,76	88,4	***	3566	3236	59,7	3543	4,2	
19				40,48	106,0	*						Tested At T + 36 hrs + 2 Cycles
20	270,5	-0,67		40,65	106,4	**	3645	3294	63,5			
21	271,8	-0,65	-0,21	29,46	77,1	***	3579	3236	62,0	3556	4,2	
22						*						Tested At T + 36 hrs + 2 Cycles
23	271,3	-0,61		41,00		**	3590	3224	66,2			
24	272,3	-0,59	-0,23	30,15		***	3560	3206	64,0	3533	4,9	
Mean 1-24	271,8						3604					

* TESTED HOT

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE A.II.39

SPECIMEN SERIES : CMY

TEMPERATURE : 100 °C

TREATMENT : DRYING DURING HEATING

Spec. No.	PULSE VELOCITY				DYNAMIC YOUNG'S MODULUS				POISSON'S RATIO			
	* m/sec	** and *** m/sec	R.R %		* GPa	** and *** GPa	R.R %		*	** and ***	R.R %	
1	4032				29,02				0,285			
2	4053				29,83				0,212			
3	4032				30,11				0,269			
Mean of 1,2,3	4040				29,65				0,275			
4												
5	4011	3544	88,7	**	28,32	23,80	83,8	**	0,282	0,213	76,1	**
6	4011	3699	92,6	***	29,92	28,13	99,0	***	0,267	0,205	73,2	***
7												
8	4011	3448	86,3	**	29,40	23,76	83,7	**	0,277	0,172	61,4	**
9	4053	3594	90,0	***	30,11	24,60	86,6	***	0,270	0,246	87,9	***
10												
11	4032	3448	86,3	**	29,91	23,04	81,1	**	0,264	0,164	58,6	**
12	3990	3512	87,9	***	29,56	23,85	84,0	***	0,265	0,234	83,6	***
13												
14	4032	3448	86,3	**	29,88	22,87	80,5	**	0,265	0,171	61,1	**
15	3990	3495	87,5	***	29,38	23,47	82,6	***	0,263	0,238	85,0	***
16												
17	3990	3432	85,9	**	30,54	22,67	79,8	**	0,253	0,183	65,4	**
18	4075	3544	88,7	***	29,75	23,03	81,1	***	0,274	0,260	92,9	***
19												
20	3969	3417	85,5	**	29,38	22,41	79,8	**	0,268	0,186	66,4	**
21	4053	3526	88,3	***	29,82	23,17	81,6	***	0,270	0,254	90,7	***
22												
23	4032	3448		**	29,86	22,27		**	0,267	0,286		**
24	4032	3448		***	29,14	23,08		***	0,272	0,225		***
Mean of 1-24	4020				29,64				0,268			

* TESTED BEFORE HEATING

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE A.II.39 (contd.)

SPECIMEN SERIES : CMY

TEMPERATURE : 150°C

TREATMENT : DRYING DURING HEATING

INITIAL WATER CONTENT = 553 g = W_t

VIZ. W_c = 284 g = 51,3%; W_n = 147 g = 26,6%; W_g = 122 g = 22,1%

Spec. No.	DEFORMATION			COMPRESSIVE STRENGTH			WATER LOSS					HEAT TREATMENT
	Initial length mm	Strain ** mm/m	Strain *** mm/m	MPa	R.R %		Mass before heat A(g)	Mass after heat B(g)	$\frac{A-B}{W_t}$ %	Mass after wett. C(g)	$\frac{A-C}{W_t}$ %	
1	271,3			38,07			3581					No Heating.
2	272,8			37,21			3609					Tested at
3	272,0			39,28			3592					Room Temp.
Mean 1,2,3	272,0			38,17			3594					
4				33,76	88,4	*						Tested Imm.
5	271,0	-0,23		38,84	101,7	**	3648	3341	65,5			Max. Temp.
6	271,0	-0,23	-0,06	30,83	80,7	***	3587	3283	55,0	3565	4,0	Attained (Time T)
7				35,74	93,6	*						Tested At
8	270,3	-0,53		38,76	101,5	**	3495	3128	66,4			T + 12 hrs
9	272,0	-0,53	-0,05	29,97	78,5	***	3633	3254	68,5	3610	4,2	
10				37,04	97,0	*						Tested At
11	273,3	-0,60		38,33	100,3	**	3631	3253	68,4			T + 24 hrs
12	272,5	-0,54	-0,09	30,32	79,4	***	3671	3300	67,1	3648	4,2	
13				38,93	101,9	*						Tested At
14	272,5	-0,62		41,08	107,5	**	3598	3221	68,2			T + 36 hrs
15	272,3	-0,62	-0,05	30,75	80,5	***	3570	3205	66,0	3551	3,4	
16				37,04	97,0	*						Tested At
17	271,0	-0,58		42,72	111,8	**	3623	3237	69,8			T + 36 hrs
18	272,8	-0,59	-0,05	27,91	73,1	***	3590	3208	69,1	3566	4,3	+ 1 cycle
19				39,79	104,2	*						Tested At
20	271,3	-0,63		42,03	110,0	**	3607	3229	68,4			T + 36 hrs
21	273,1	-0,62	-0,06	27,92	72,8	***	3612	3233	68,5	3597	2,7	+ 2 Cycles
22						*						Tested At
23	271,8	-0,68		39,62		**	3598	3210	70,2			T + 36 hrs
24	271,3	-0,70	-0,09	28,25		***	3502	3126	68,0	3484	3,3	+ 2 Cycles
Mean 1-24	271,9						3598					

* TESTED HOT

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE A.II.40

SPECIMEN SERIES : CMY

TEMPERATURE : 150°C

TREATMENT : DRYING DURING HEATING

Spec. No.	PULSE VELOCITY				DYNAMIC YOUNG'S MODULUS				POISSON'S RATIO			
	* m/sec	** and *** m/sec	R.R %		* GPa	** and *** GPa	R.R %		*	** and ***	R.R %	
1	3969				29,52							
2	3969				30,11							
3	4032				30,20							
Mean of 1,2,3	3990				29,94							
4												
5	3990	3342	83,7	**	31,10	22,28	78,5	**	0,244	0,159	56,8	**
6	3969	3495	87,5	***	29,99	22,64	79,7	***	0,249	0,260	92,9	***
7												
8	3948	3229	80,8	**	28,23	18,93	66,7	**	0,262	0,190	67,9	**
9	3990	3464	86,7	***	30,85	23,39	82,4	***	0,244	0,237	84,6	***
10												
11	3990	3243	81,2	**	30,43	19,30	68,0	**	0,249	0,204	72,9	**
12	4011	3479	87,1	***	30,20	23,13	81,4	***	0,265	0,253	90,4	***
13												
14	4011	3256	81,5	**	30,07	19,66	69,2	**	0,257	0,190	67,9	**
15	3969	3495	87,1	***	29,35	21,91	77,3	***	0,255	0,270	96,4	***
16												
17	3969	3215	80,5	**	30,47	20,13	70,9	**	0,256	0,150	53,6	**
18	3928	3387	84,8	***	28,90	21,12	74,4	***	0,254	0,260	92,9	***
19												
20	3928	3188	79,8	**	29,63	19,75	69,5	**	0,247	0,149	53,2	**
21	3990	3448	86,3	***	30,06	22,41	78,9	***	0,253	0,251	89,6	***
22												
23	3928	3175		**	29,52	18,79		**	0,246	0,158		**
24	3928	3432		***	28,51	21,26		***	0,192	0,260		***
Mean of 1-24	3968				29,81				0,248			

* TESTED BEFORE HEATING

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE A.II.40 (contd.)

SPECIMEN SERIES : CMY

TEMPERATURE : 250°C

TREATMENT : DRYING DURING HEATING

INITIAL WATER CONTENT = 553 g = W_t

VIZ. W_c = 248 g = 51,3%

W_n = 147 g = 26,6%

W_g = 122 g = 22,1%

Spec. No.	DEFORMATION			COMPRESSIVE STRENGTH			WATER LOSS					HEAT TREATMENT
	Initial length mm	Strain ** mm/m	Strain *** mm/m	MPa	R.R %		Mass before heat A(g)	Mass after heat B(g)	$\frac{A-B}{W_t}$ %	Mass after wett. C(g)	$\frac{A-C}{W_t}$ %	
1	270,8			38,59			3604					No Heating.
2	272,4			42,03			3663					Tested at
3	269,5			39,62			3572					Room Temp.
Mean 1,2,3	270,9			40,07			3613					
4				40,83	106,9	*						Tested Imm.
5	270,0	-0,16		34,80	91,1	**	3568	3174	71,2			Max. Temp.
6	268,5	-0,16	0,52	31,70	83,0	***	3579	3195	69,4	3541	6,9	Attained (Time T)
7				42,55	111,4	*						Tested At
8	271,0	-0,24		34,97	91,5	**	3639	3239	72,3			T + 12 hrs
9	269,5	-0,30	0,72	26,70	69,9	***	3564	3164	72,3	3534	5,4	
10				43,75	114,5	*						Tested At
11	270,5	-0,22		33,94	88,8	**	3628	3220	73,8			T + 24 hrs
12	271,8	-0,25	0,71	26,87	70,3	***	3664	3251	74,7	3631	6,0	
13				38,33	100,3	*						Tested At
14	271,3	-0,39		35,14	92,0	**	3570	3169	72,5			T + 36 hrs
15	272,8	-0,41	0,55	28,77	75,3	***	3616	3212	73,1	3583	6,0	
16				41,34	108,2	*						Tested At
17	270,3	-0,46		37,72	98,7	**	3570	3165	73,2			T + 36 hrs
18	269,2	-0,40	0,76	27,22	71,3	***	3576	3167	74,0	3545	5,6	+ 1 cycle
19				40,48	106,0	*						Tested At
20	270,3	-0,39		35,66	93,4	**	3569	3169	72,3			T + 36 hrs
21	269,2	-0,45	0,48	29,11	76,2	***	3556	3155	72,5	3524	5,8	+ 2 Cycles
22						*						Tested At
23	270,5	-0,38		34,97		**	3643	3225	75,6			T + 36 hrs
24	270,3	-0,42	0,56	28,42		***	3635	3223	74,5	3601	6,1	+ 2 Cycles
Mean 1-24	270,3						3598					

* TESTED HOT

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE A.II.41

SPECIMEN SERIES : CMY

TEMPERATURE : 250°C

TREATMENT : DRYING DURING HEATING

Spec. No.	PULSE VELOCITY				DYNAMIC YOUNG'S MODULUS				POISSON'S RATIO			
	* m/sec	** and *** m/sec	R.R %		* GPa	** and *** GPa	R.R %		*	** and ***	R.R %	
1	4032				32,10				0,231			
2	4097				30,74				0,275			
3	4075				29,69				0,274			
Mean of 1,2,3	4068				30,84				0,260			
4												
5	4097	2843	71,2	**	29,90	13,99	49,3	**	0,280	0,235	83,9	**
6	4097	3495	87,5	***	30,99	20,15	71,0	***	0,268	0,308	110,0	***
7												
8	4075	2897	72,5	**	32,13	14,00	49,3	**	0,248	0,264	94,3	**
9	4075	3512	87,9	***	29,90	19,89	70,0	***	0,275	0,313	111,8	***
10												
11	4053	2801	70,1	**	30,46	12,79	45,0	**	0,269	0,273	97,5	**
12	4097	3512	87,9	***	32,11	20,75	73,1	***	0,256	0,306	109,3	***
13												
14	4053	2771	69,4	**	29,70	12,57	44,3	**	0,271	0,262	93,6	**
15	4097	3561	89,1	***	30,07	21,62	76,1	***	0,279	0,295	105,4	***
16												
17	4097	2712	67,9	**	29,59	11,99	42,2	**	0,284	0,265	94,6	**
18	4075	3561	89,1	***	31,23	20,78	73,2	***	0,257	0,309	110,4	***
19												
20	4075	2843	71,2	**	30,72	12,63	44,5	**	0,262	0,284	101,4	**
21	4097	3544	88,7	***	29,54	20,99	73,9	***	0,285	0,301	107,5	***
22												
23	4053	2791		**	30,58	12,53		**	0,269	0,301		**
24	4075	3544		***	30,54	21,34		***	0,273	0,301		***
Mean of 1-24	4080				30,54				0,270			

* TESTED BEFORE HEATING

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE A.II.41 (contd.)

SPECIMEN SERIES : CMY

TEMPERATURE : 400°C

TREATMENT : DRYING DURING HEATING

INITIAL WATER CONTENT = 553 g = W_t

VIZ. W_c = 248 g = 51,3%; W_n = 147 g = 26,6%; W_g = 122 g = 22,1%

Spec. No.	DEFORMATION			COMPRESSIVE STRENGTH			WATER LOSS					HEAT TREATMENT
	Initial length mm	Strain ** mm/m	Strain *** mm/m	MPa	R.R %		Mass before heat A(g)	Mass after heat B(g)	$\frac{A-B}{W_t}$ %	Mass after wett. C(g)	$\frac{A-C}{W_t}$ %	
1	272,7			35,66			3591					No Heating. Tested at Room Temp.
2	270,9			33,08			3542					
3	271,4			36,00			3571					
Mean 1,2,3	271,7			34,97			3568					
4				32,21	84,3	*						Tested Imm. Max. Temp. Attained (Time T)
5	272,8	1,61		27,73	72,6	**	3588	3152	78,8			
6	272,8	1,17	2,93	24,81	64,9	***	3586	3142	80,3	3573	2,4	
7				34,80	91,1	*						Tested At T + 12 hrs
8	269,7	1,32		25,67	67,2	**	3573	3126	80,8			
9	272,3	2,16	3,71	26,01	68,1	***	3563	3113	81,4	3560	0,5	
10				34,80	91,1	*						Tested At T + 24 hrs
11	274,6	1,50		22,91	60,0	**	3569	3110	83,0			
12	272,8	1,42	3,09	24,29	63,6	***	3559	3103	82,5	3543	2,9	
13				30,66	80,3	*						Tested At T + 36 hrs
14	273,3	1,84		22,39	58,6	**	3566	3105	83,4			
15	271,3	1,43	2,94	26,36	69,0	***	3547	3107	79,6	3534	2,4	
16				31,35	82,1	*						Tested At T + 36 hrs + 1 cycle
17	275,3	1,94		26,01	68,1	**	3605	3147	82,8			
18	273,6	1,67	3,46	24,81	64,9	***	3583	3127	82,5	3580	0,5	
19				33,76	88,4	*						Tested At T + 36 hrs + 2 Cycles
20	273,1	1,66		25,84	67,6	**	3589	3131	82,8			
21	271,5	1,60	2,98	21,53	56,4	***	3553	3103	81,4	3537	2,9	
22						*						Tested At T + 36 hrs + 2 Cycles
23	273,6	1.85		24,98		**	3561	3110	81,6			
24	272,5	1,84	3,08	23,60		***	3614	3162	81,7	3608	1,1	
Mean 1-24	272,8						3571					

* TESTED HOT

** TESTED COLD AFTER HEATING

*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE A.II.42

SPECIMEN SERIES : CMY

TEMPERATURE : 400 °C

TREATMENT : DRYING DURING HEATING

Spec. No.	PULSE VELOCITY				DYNAMIC YOUNG'S MODULUS				POISSON'S RATIO			
	* m/sec	** and *** m/sec	R.R %		* GPa	** and *** GPa	R.R %		*	** and ***	R.R %	
1	3868				25,03				0,286			
2	3888				26,36				0,284			
3	3888				27,24				0,273			
Mean of 1,2,3	3882				26,21				0,286			
4												
5	3928	2027	50,7	**	26,78	5,86	20,6	**	0,288	0,312	111,4	**
6	3928	3577	89,5	***	25,67	17,88	63,0	***	0,304	0,351	125,4	***
7												
8	3928	2016	50,5	**	26,28	5,87	20,7	**	0,298	0,309	110,4	**
9	3888	3611	90,4	***	25,79	18,84	66,3	***	0,293	0,343	122,4	***
10												
11	3868	1939	48,5	**	24,40	5,27	18,6	**	0,307	0,311	111,1	**
12	3848	3479	87,1	***	24,79	17,84	62,8	***	0,300	0,336	120,0	***
13												
14	3829	1891	47,3	**	24,57	4,77	16,8	**	0,300	0,327	116,8	**
15	3868	3594	90,0	***	25,69	18,42	64,9	***	0,290	0,345	123,2	***
16												
17	3868	1823	45,6	**	25,52	4,89	17,2	**	0,293	0,372	132,9	**
18	3868	3577	89,5	***	25,61	18,82	66,3	***	0,291	0,339	121,1	***
19												
20	3848	1827	45,7	**	24,87	4,78	16,8	**	0,300	0,308	110,0	**
21	3848	3464	86,7	***	23,94	14,44	50,8	***	0,312	0,379	135,4	***
22												
23	3810	1801		**	23,85	4,20		**	0,305	0,335		**
24	3829	3544		***	24,93	18,68		***	0,299	0,339		***
Mean of 1-24	3864				25,08				0,299			

* TESTED BEFORE HEATING

** TESTED COLD AFTER HEATING

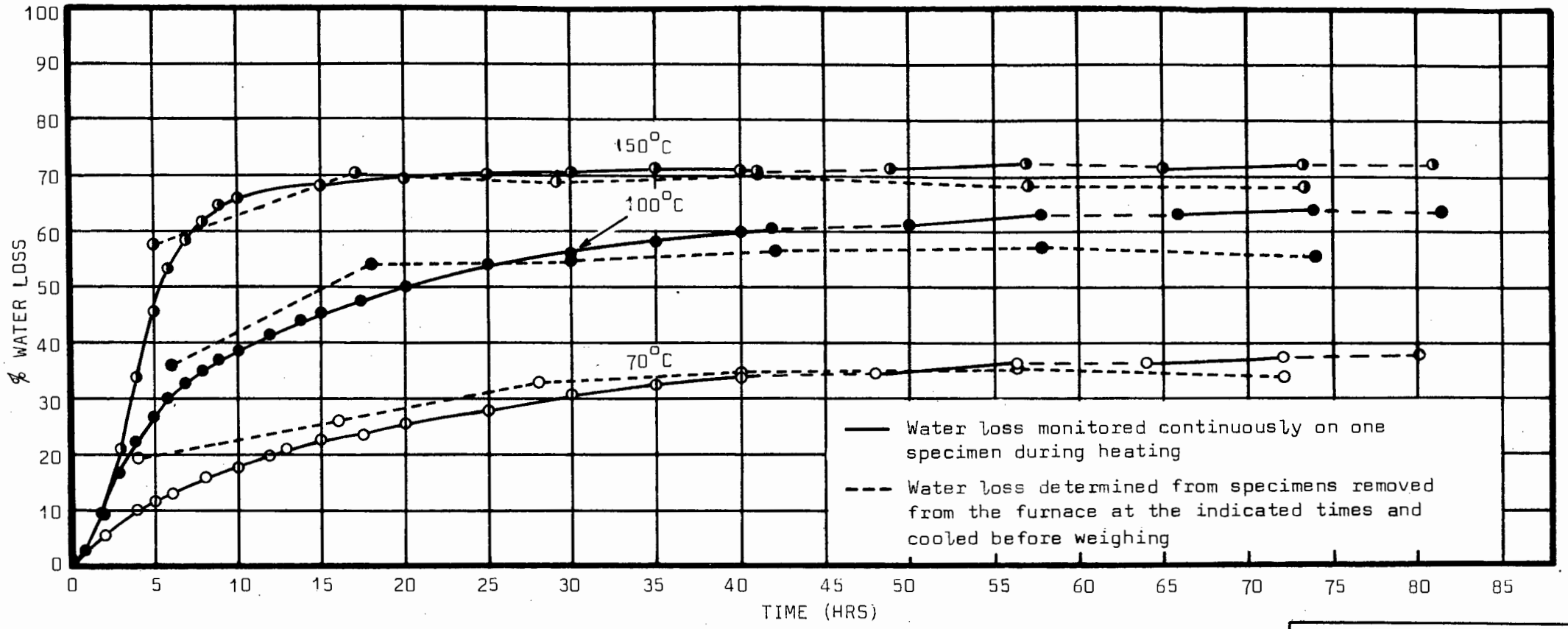
*** TESTED COLD AFTER HEATING AND 7 DAYS IN WATER

TABLE A.II.42 (contd.)

APPENDIX III

The percentage water loss of test specimens at the various temperature levels. (Water loss continuously monitored on one test specimen during the heating period).

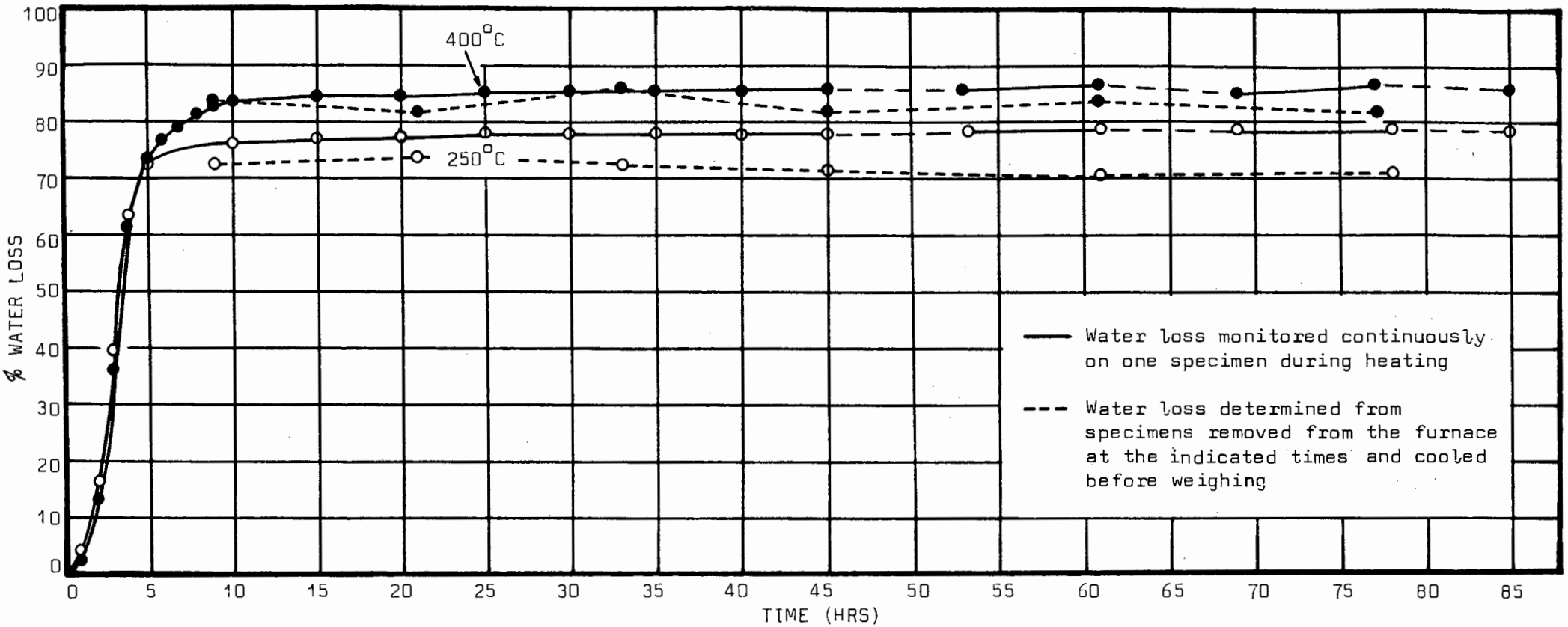
Figure.A.III.1 : 70°C; 100°C; 150°C	Mix BCY	
Figure.A.III.2 : 150°C; 400°C		
Figure.A.III.3 : 70°C; 100°C; 150°C	Mix CCX	
Figure.A.III.4 : 250 C; 400°C		
Figure.A.III.5 : 70°C; 100°C; 150°C	Mix CCY	
Figure.A.III.6 : 250°C; 400°C		
Figure.A.III.7 : 70°C; 100°C; 150°C	Mix BMY	
Figure.A.III.8 : 250°C; 400°C		
Figure.A.III.9 : 70°C; 100°C; 150°C	Mix CMX	
Figure.A.III.10: 250°C; 400°C		
Figure.A.III.11: 70°C; 100°C; 150°C	Mix CMY	
Figure.A.III.12: 250°C; 400°C		



																				Temperature Cycling				
TIME(HRS)	0	1	2	3	4	5	6	7	8	9	10	12	14	16	20	25	30	35	40	C	H	C	H	C
70°C	0	3,0	5,4	7,8	9,6	11,2	12,8	14,1	15,8	16,8	17,8	19,5	21,6	17,9	25,5	27,6	30,5	32,4	33,8	34,5	36,2	36,5	37,6	38,1
100°C	0	3,6	9,8	17,1	22,8	26,8	30,4	33,1	35,1	37,2	39,0	41,8	44,5	46,5	50,4	54,0	56,5	58,2	59,5	61,1	63,3	63,3	64,1	63,6
150°C	0	3,0	9,3	20,7	33,8	45,4	53,2	58,2	61,9	64,1	65,6	66,3	67,6	68,0	69,1	70,0	70,1	70,1	70,3	71,1	72,0	71,1	71,9	72,0

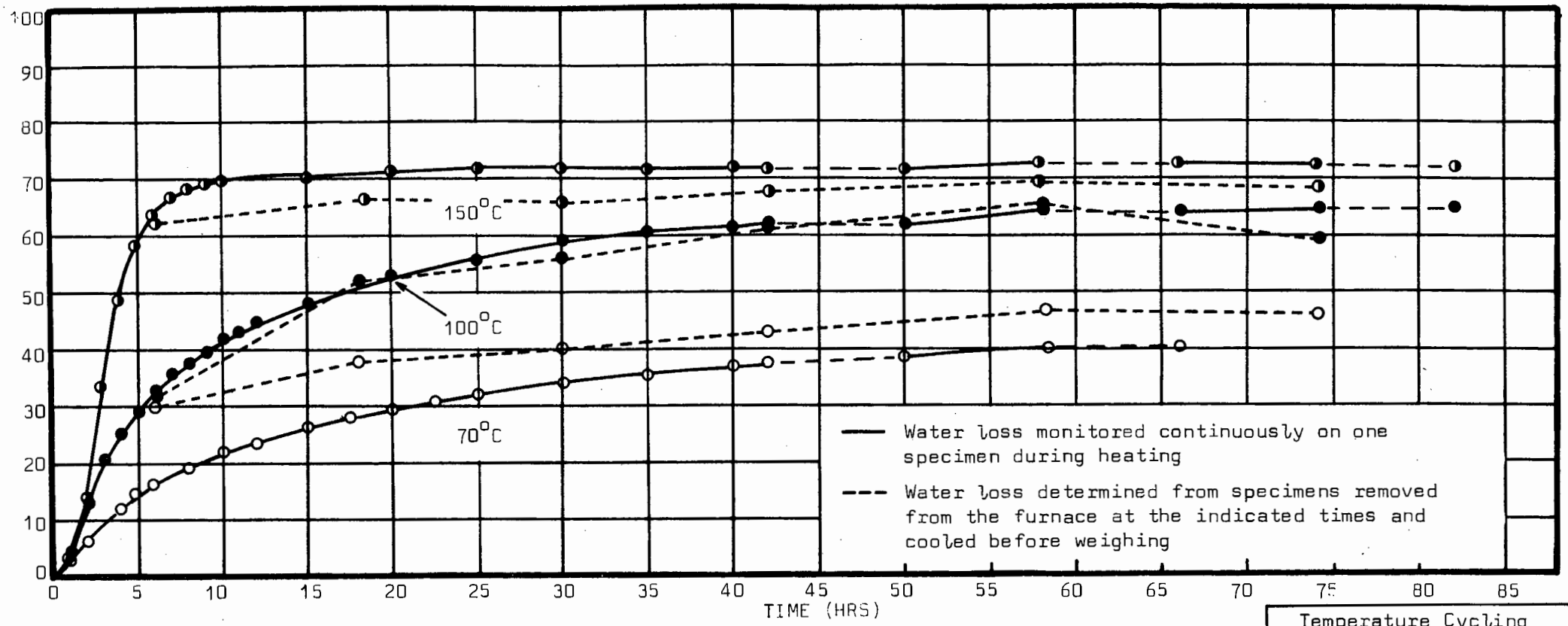
Values for water loss monitored continuously on one specimen during heating.

FIG.A.III.1: Water loss at temperatures of 70°C,100°C, and 150°C: Mix BCY



	Values for water loss monitored continuously on one specimen during heating																		Temperature Cycling				
TIME(HRS)	1	2	3	4	5	6	7	8	9	10	12	20	25	30	35	40	45	46	C	H	C	H	C
250°C	4,0	16,5	39,3	63,4	72,0	74,1	75,4	75,9	76,0	76,0	76,2	77,0	77,2	77,6	77,7	77,7	77,7		78,1	78,8	78,2	78,7	78,7
400°C	3,0	13,8	36,5	62,2	73,3	77,2	79,9	81,9	83,2	84,0		84,9	85,6	85,9	86,0	86,1	86,5		86,2	87,0	85,9	87,3	85,8

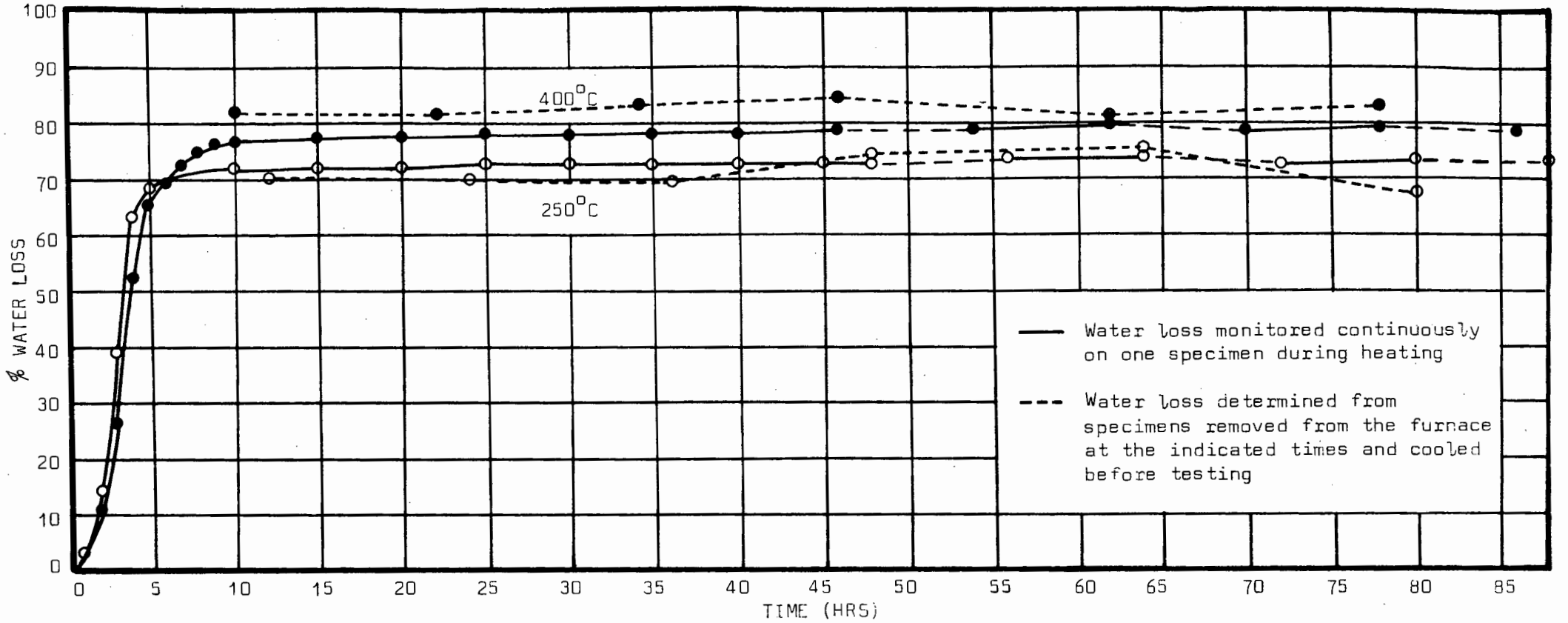
FIG.A.III.2: Water loss at temperatures of 250°C and 400°C : Mix BCY



TIME(HRS)	1	2	3	4	5	6	7	8	9	10	12	14	16	20	25	30	35	40	41	42	Temperature Cycling C	H	C	H	C
70°C	3,6	7,1	10,1	12,9	14,8	16,8	18,3	19,6	21,1	22,2	23,9	25,5	27,1	29,4	32,2	34,2	35,4	36,9	37,6		38,6	40,1	Oven Failure		
100°C	4,7	13,3	20,4	25,3	29,2	32,7	35,5	37,7	39,7	41,7	44,5	46,0	47,0	52,9	56,5	58,7	60,3	61,2	61,9		62,5	64,1	63,8	64,5	64,5
150°C	3,4	13,7	33,2	48,7	58,1	63,8	66,9	68,2	69,1	69,3				71,0	71,8	71,9				72,0	72,0	72,9	72,9	72,9	72,7

Values for water loss monitored continuously on one specimen during heating.

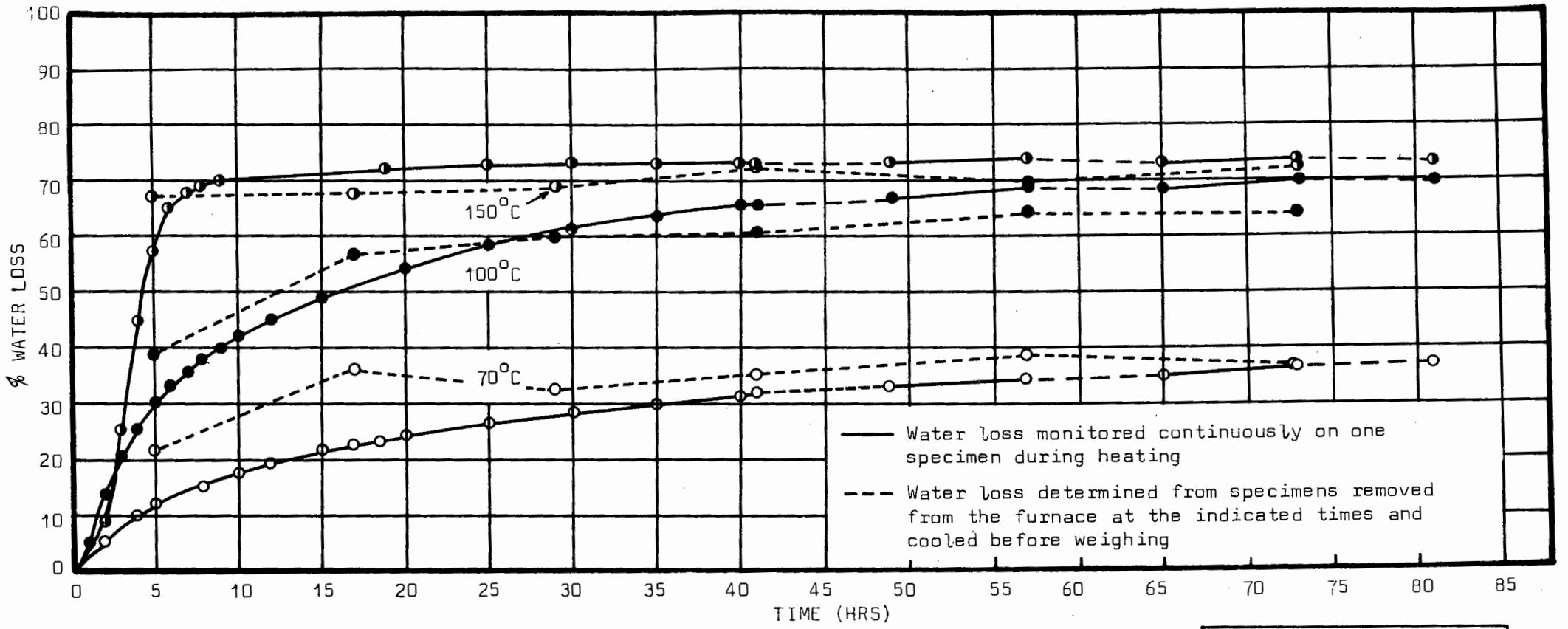
FIG.A.III.3: Water loss at temperatures of 70°C, 100°C and 150°C : Mix CCX.



Values for water loss monitored continuously on one specimen during heating.

																						Temperature Cycling				
TIME(HRS)	1	2	3	4	5	6	8	10	12	14	16	20	25	30	35	40	41	42	44	45	46	C	H	C	H	C
250°C	3,7	14,4	39,0	63,4	66,8	70,1	70,9	71,6	71,7	71,8	71,9	72,0	72,5	72,7	72,7	72,7	72,7	72,7	72,7	72,7	72,7	73,4	73,7	72,7	73,6	73,6
400°C	3,1	10,6	26,6	62,3	65,6	69,2	74,6	76,7	76,9	77,0	77,1	77,2	77,6	77,8	79,0	78,0	78,0	78,0	78,1	78,2	78,2	78,8	79,2	78,4	79,1	78,9

FIG.A.III.4: Water loss at temperatures of 250°C and 400°C : Mix CCX.



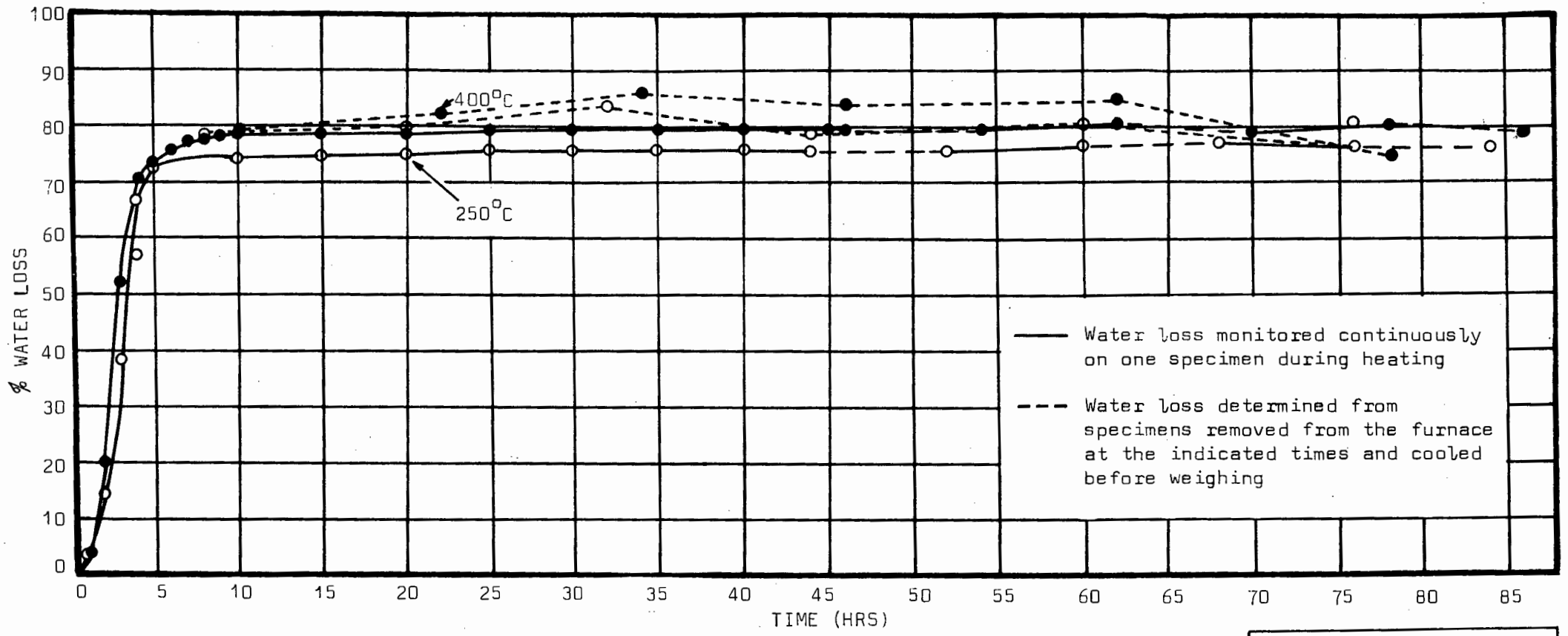
Values for water loss monitored continuously on one specimen during heating

TIME(HRS)	1	2	3	4	5	6	7	8	9	10	12	14	16	20	25	30	35	40	41
70°C	2,9	5,0	7,9	10,0	11,5	12,9	14,0	15,0	16,1	17,0	19,1	20,4	22,0	24,1	25,9	28,1	29,0	30,0	31,1
100°C	5,0	13,4	20,4	25,5	29,6	32,8	35,4	37,9	39,9	41,9	44,9	47,5	50,0	54,1	58,1	61,0	63,3	65,2	65,3
150°C	3,0	9,0	24,9	44,9	57,1	64,9	67,8	69,0	69,8	69,9	70,0		70,9	71,9	72,8	72,8	72,8	72,8	72,8

Temperature Cycling

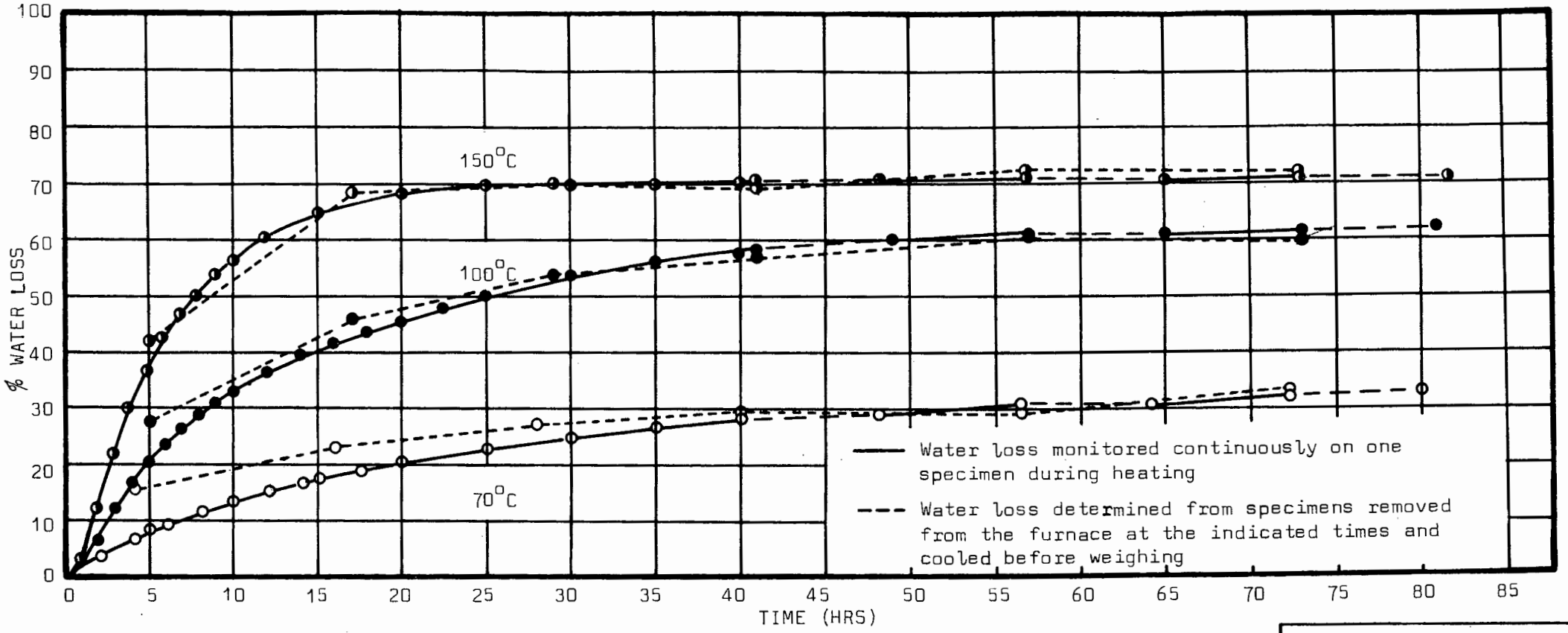
C	H	C	H	C
32,5	33,9	34,6	36,0	36,6
66,6	68,6	68,1	69,8	69,6
72,8	73,3	72,8	73,3	78,9

FIG.A.III.5: Water loss at temperatures of 70°C, 100°C and 150°C : Mix CCY.



	Values for water loss monitored continuously on one specimen during heating																		Temperature Cycling				
TIME(HRS)	1	2	3	4	5	6	7	8	9	10	20	25	30	35	40	44	45	46	C	H	C	H	C
250°C	3,7	14,5	38,9	67,1	72,8	74,0	74,4			74,5	74,9	75,6	75,8	75,8	75,8	75,8			75,8	76,7	75,8	77,3	76,7
400°C	3,8	19,9	52,2	70,8	73,6	75,8	77,4	77,9	78,3	78,4	78,7	79,2	79,7	79,7	79,7		79,8	79,8	79,7	80,5	79,7	80,7	79,9

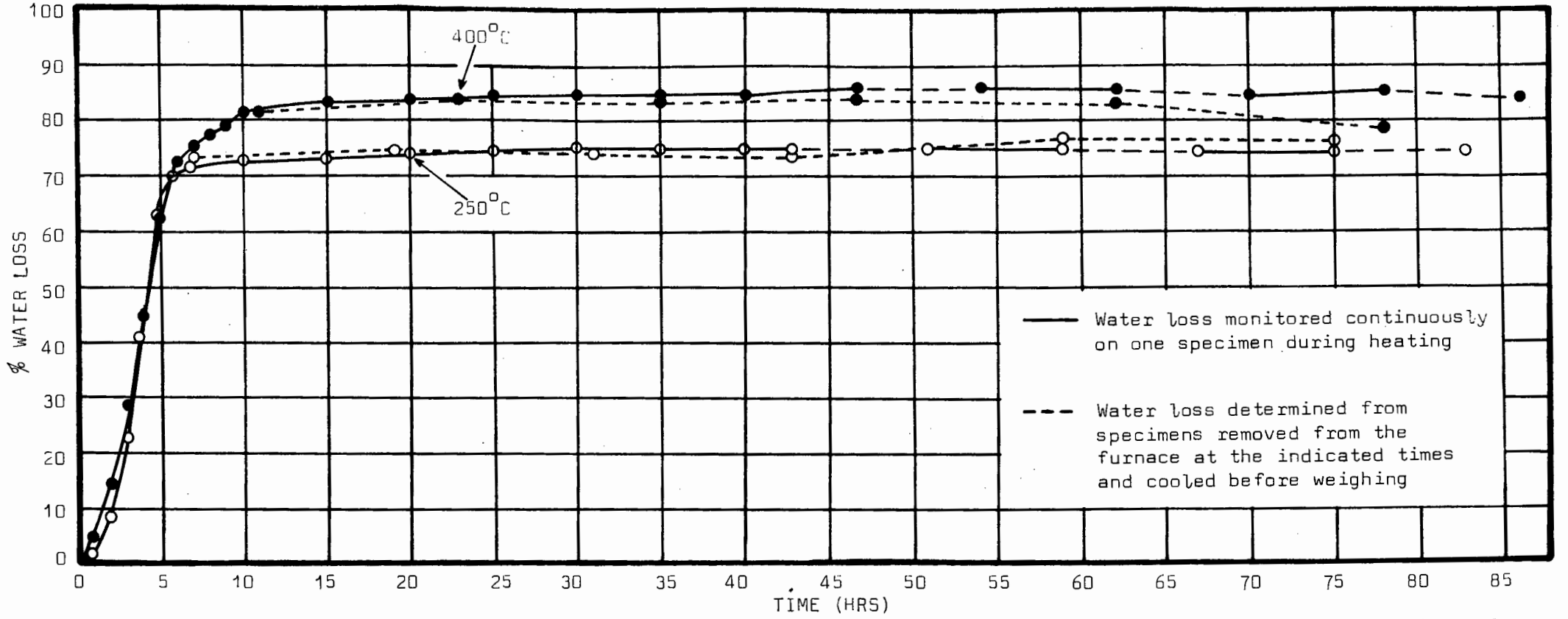
FIG.A.III.6: Water loss at temperatures of 250°C and 400°C : Mix CCY.



Values for water loss monitored continuously on one specimen during heating.

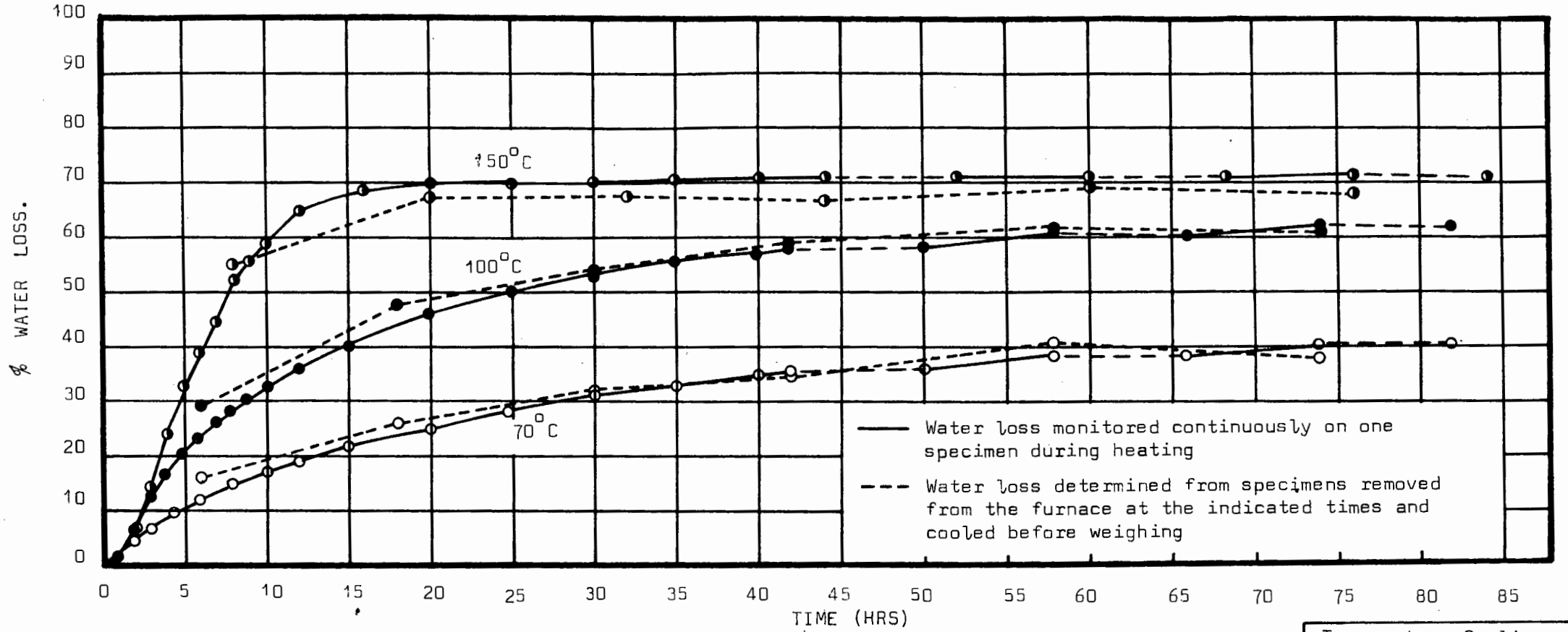
TIME (HRS)	0	1	2	3	4	5	6	7	8	9	10	12	14	16	20	25	30	35	40	41	Temperature Cycling C	H	C	H	C
70°C	0	2,0	3,3	5,1	6,6	8,4	9,5	10,4	11,5	12,2	13,5	14,9	16,4	17,8	20,1	21,5	24,6	26,1	28,1		23,9	30,5	30,5	32,3	33,1
100°C	0	1,4	6,2	12,0	16,5	20,3	23,6	26,3	28,8	30,8	32,8	36,2	39,0	41,2	45,4	50,0	53,3	55,9	57,9	58,2	59,1	61,0	61,0	62,9	62,2
150°C	0	3,7	12,3	22,3	30,2	37,0	42,4	46,9	50,6	53,7	56,5	60,3	63,5	65,9	68,1	69,4	69,9	70,1	70,3	70,3	70,6	70,9	70,7	71,1	71,1

FIG.A.III.7: Water loss at temperatures of 70°C, 100°C and 150°C : Mix BMY.



	Values for water loss monitored continuously on one specimen during heating																	Temperature Cycling				
TIME(HRS)	1	2	3	4	5	6	7	8	9	10	20	25	30	35	40	43	46	C	H	C	H	C
250°C	1,7	8,5	22,3	40,3	63,1	69,9	71,2			72,3	73,5	74,1	74,4	74,5	74,5	75,6		74,7	74,8	74,3	74,1	74,6
400°C	3,8	14,1	28,1	44,2	61,9	72,2	75,0	76,8	78,9	81,2	83,2	83,7	84,2	84,4	84,4		84,6	84,6	84,3	84,4	85,4	84,8

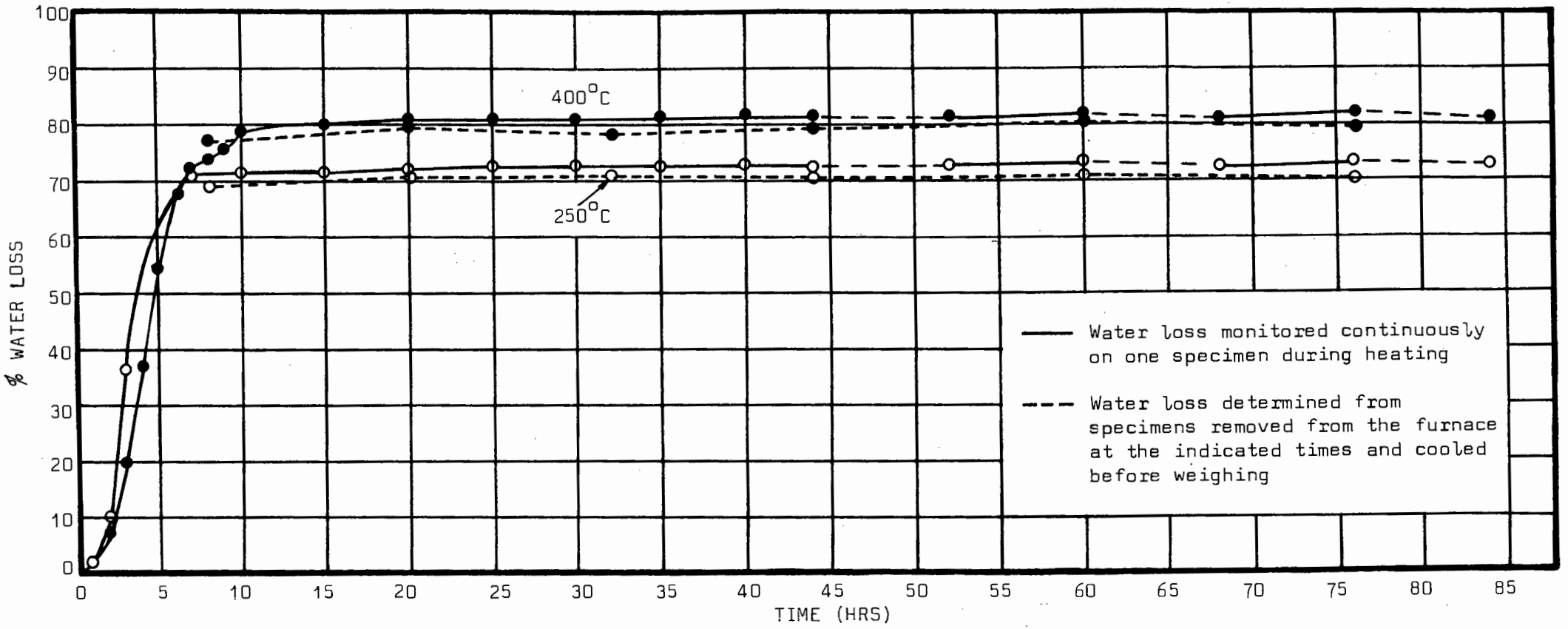
FIG.A.III.8: Water loss at temperatures of 250°C and 400°C : Mix BMY.



																					Temperature Cycling				
TIME (HRS)	1	2	3	4	5	6	7	8	10	12	14	16	20	25	30	35	40	41	42	44	C	H	C	H	C
70°C	2,1	4,2	6,5	9,5	10,5	11,9	13,3	14,5	16,8	18,8	20,0	22,0	24,5	27,8	30,5	32,2	34,4	34,8	35,0		35,8	37,9	38,0	39,8	40,0
100°C	1,9	7,1	12,7	17,0	20,5	23,7	26,4	28,6	32,8	36,2	39,1	41,9	46,1	50,2	53,3	55,7	57,1		58,2		58,8	60,8	60,8	62,3	62,3
150°C	1,4	6,1	13,7	23,8	32,3	38,7	44,1	50,2	58,9	64,3	67,9	68,2	69,0	69,7	70,0	70,2	70,3			70,4	70,7	71,0	71,0	71,0	71,2

Values for water loss monitored continuously on one specimen during heating.

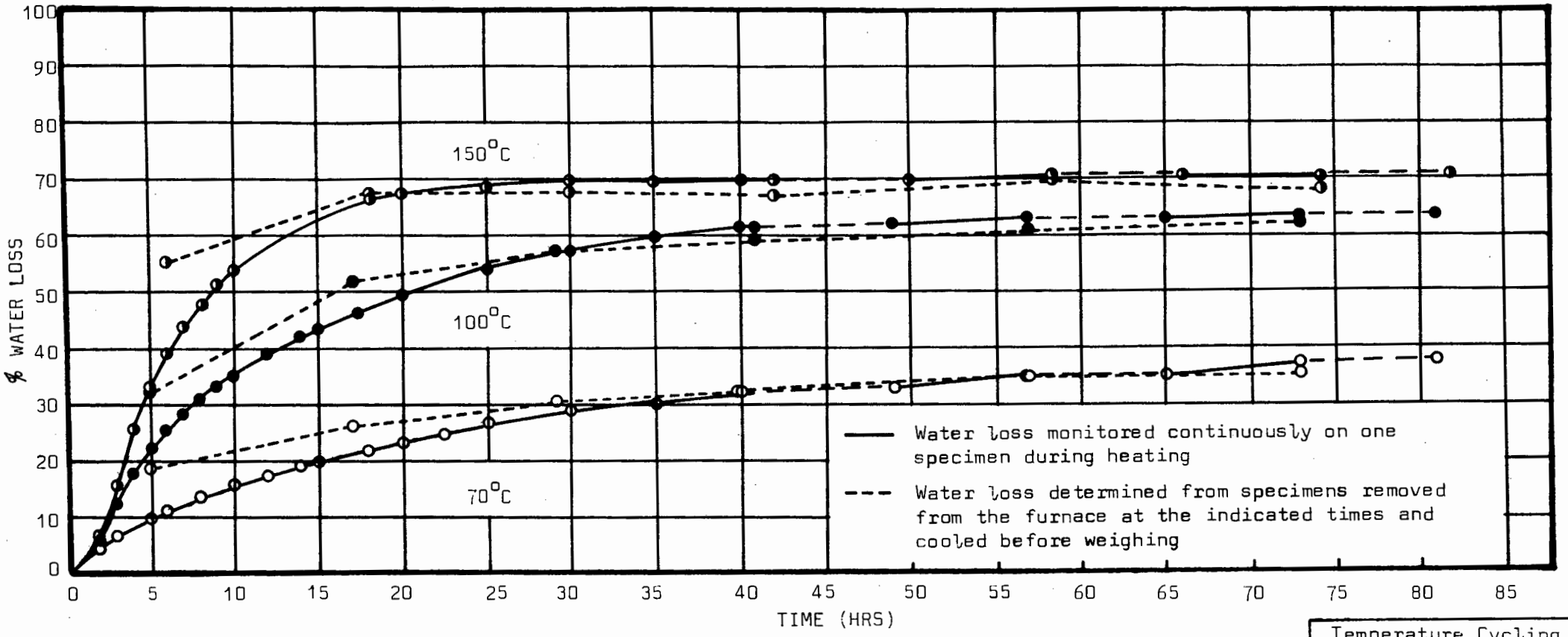
FIG.A.III.9: Water loss at temperatures of 70°C, 100°C and 150°C : Mix CMX.



Values for water loss monitored continuously on one specimen during heating

TIME(HRS)	1	2	3	4	5	6	7	8	10	12	14	16	20	25	30	35	40	41	42	43	44	Temperature Cycling C	H	C	H	C
250°C	2,0	10,1	36,5	53,0	62,5	67,9	71,0	71,1	71,5	71,2	71,5	71,7	72,0	72,4	72,5	72,7	72,8	72,8	72,8	72,8	72,8	73,0	73,4	73,0	73,8	73,5
400°C	1,8	7,0	19,3	36,1	54,0	67,4	71,5	73,5	78,0	78,9	79,5	79,9	80,2	80,5	80,6	80,9	81,0				81,1	80,8	81,8	80,9	81,9	81,1

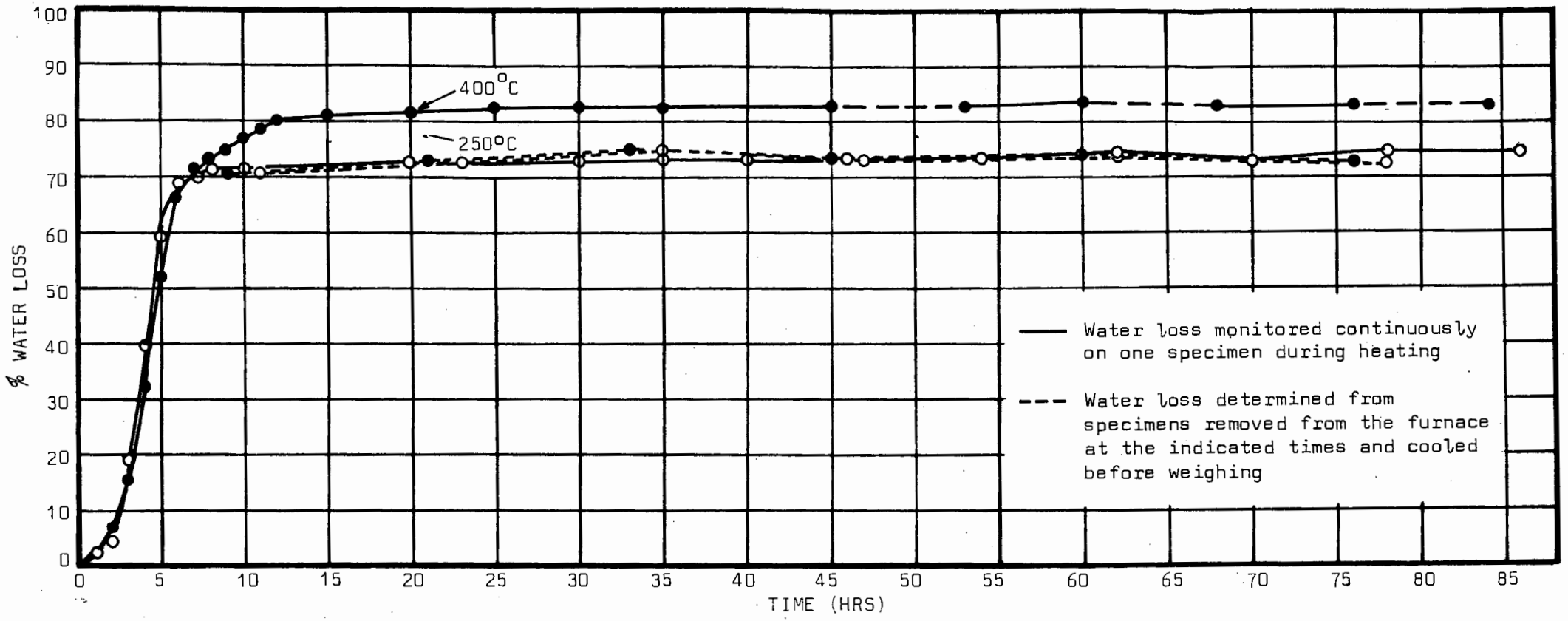
FIG.A.III.10: Water loss at temperatures of 250°C and 400°C : Mix CMX



																						Temperature Cycling				
TIME (HRS)	0	1	2	3	4	5	6	7	8	9	10	12	14	16	20	25	30	35	40	41	42	C	H	C	H	C
70°C	0	2,9	4,3	6,5	8,6	9,5	11,0	12,1	13,5	14,4	15,4	17,1	18,6	20,1	22,9	16,1	28,3	29,9	31,5	31,9		32,9	34,5	34,5	36,8	37,4
100°C	0	1,8	6,5	13,3	18,6	22,7	26,0	29,0	31,5	33,9	35,8	39,4	42,3	45,0	49,5	54,2	57,4	59,6	61,2	61,7		62,2	63,2	63,0	63,8	63,8
150°C	0	2,3	6,8	15,7	25,5	33,0	39,0	43,7	47,6	51,0	53,8	58,0	61,1	64,0	67,3	68,6	69,1	69,3	69,4		69,4	69,9	70,5	70,5	70,5	70,7

Values for water loss monitored continuously on one specimen during heating.

FIG.A.III.11: Water loss at temperatures of 70°C, 100°C and 150°C : Mix CMY.



	Values for water loss monitored continuously on one specimen during heating																		Temperature Cycling				
TIME(HRS)	1	2	3	4	5	6	7	8	9	10	12	20	25	30	35	40	45	46	C	H	C	H	C
250°C	1,8	4,9	19,1	39,3	59,2	68,7	70,0	70,6		71,1		72,0		72,8	72,9	72,9		73,1	73,6	74,0	73,6	74,4	74,2
400°C	2,2	6,8	15,4	32,0	51,5	66,2	71,1	72,8	74,3	76,5	79,9	81,4	81,9	82,1	82,3		82,3		82,6	83,5	82,5	83,3	83,0

FIG.A.III.12: Water loss at temperatures of 250°C and 400°C : Mix CMY.

APPENDIX IV

The linear deformation of test specimens heated to the various test temperatures.

(i)	Figure	A.IV.1	to	Figure	A.IV.7	: Mix BCY	CONCRETE MIXES
(ii)	Figure	A.IV.8	to	Figure	A.IV.14	: Mix CCX	
(iii)	Figure	A.IV.15	to	Figure	A.IV.21	: Mix CCY	
(iv)	Figure	A.IV.22	to	Figure	A.IV.28	: Mix BMY	MORTAR MIXES
(v)	Figure	A.IV.29	to	Figure	A.IV.35	: Mix CMX	
(vi)	Figure	A.IV.36	to	Figure	A.IV.42	: Mix CMY	

For each of (i) to (vi) above the linear deformation curves are given in the following order:
70°C (fully saturated); 100°C (fully saturated); 70°C (dry); 100°C (dry); 150°C (dry); 250°C (dry); 400°C (dry).

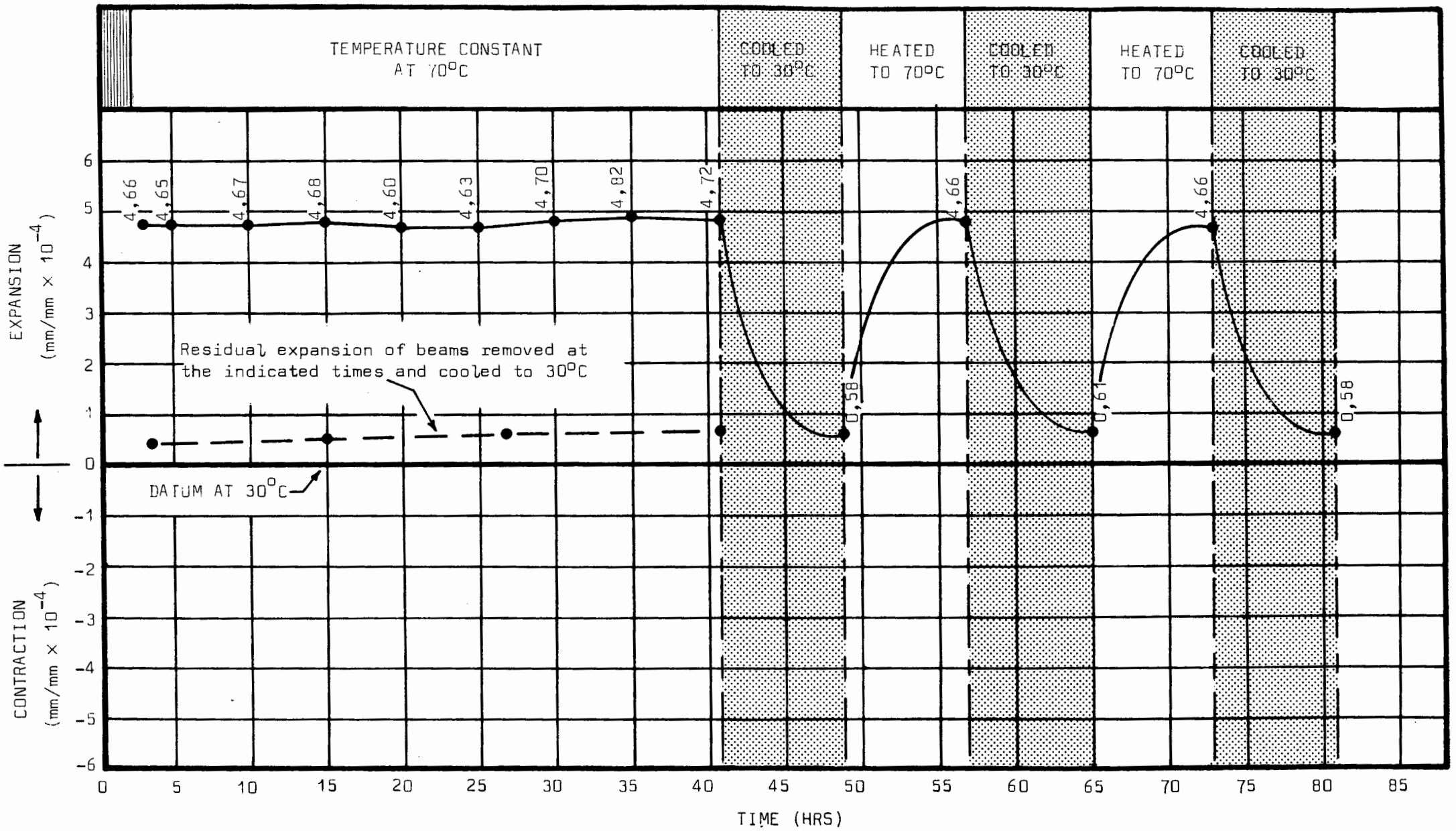


FIG.A.IV.1: The linear deformation of test specimen : Mix BCY at 70°C (saturated).

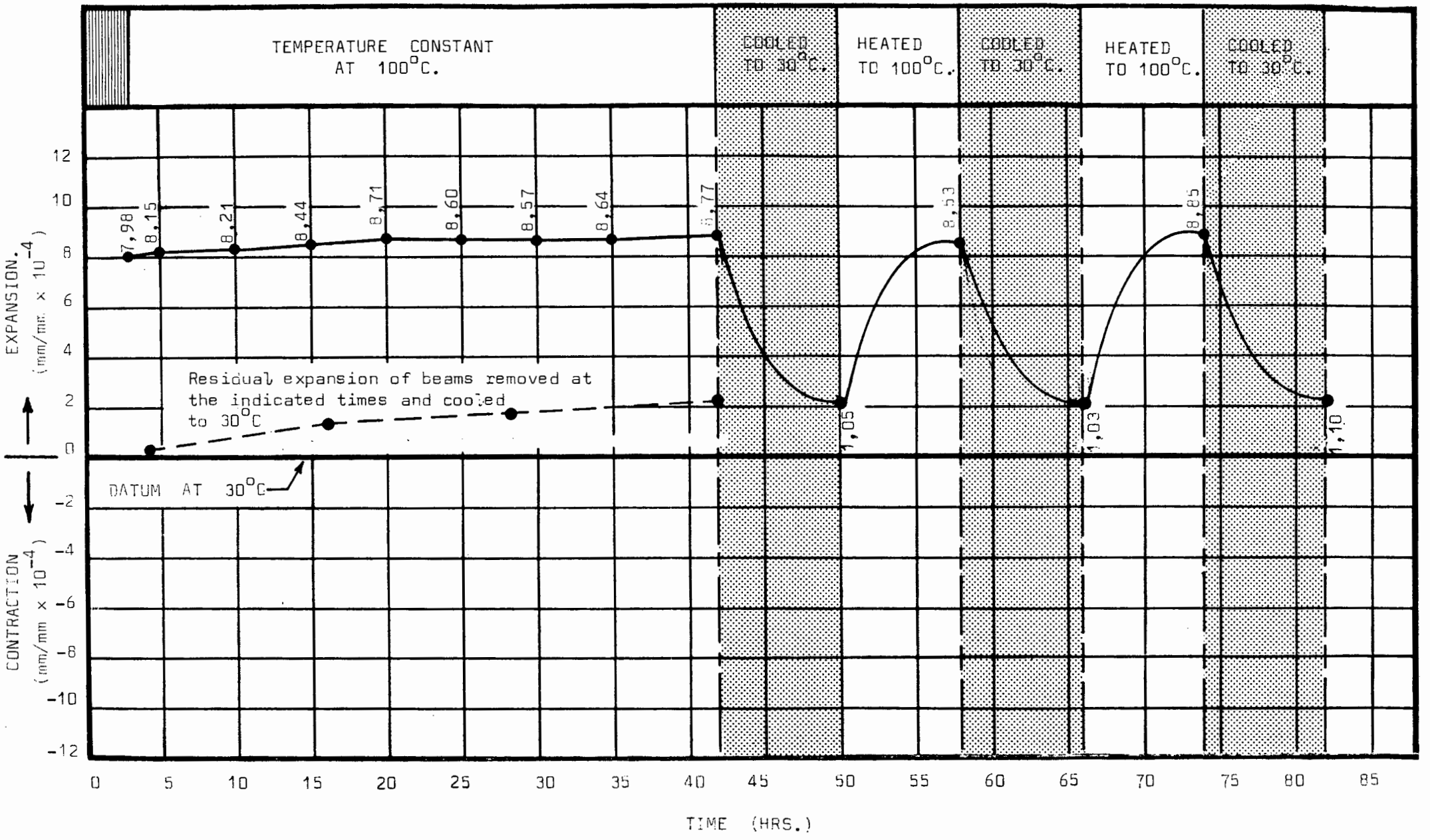


FIG.A.IV.2: The linear deformation of test specimen: Mix BCY at 100°C (saturated).

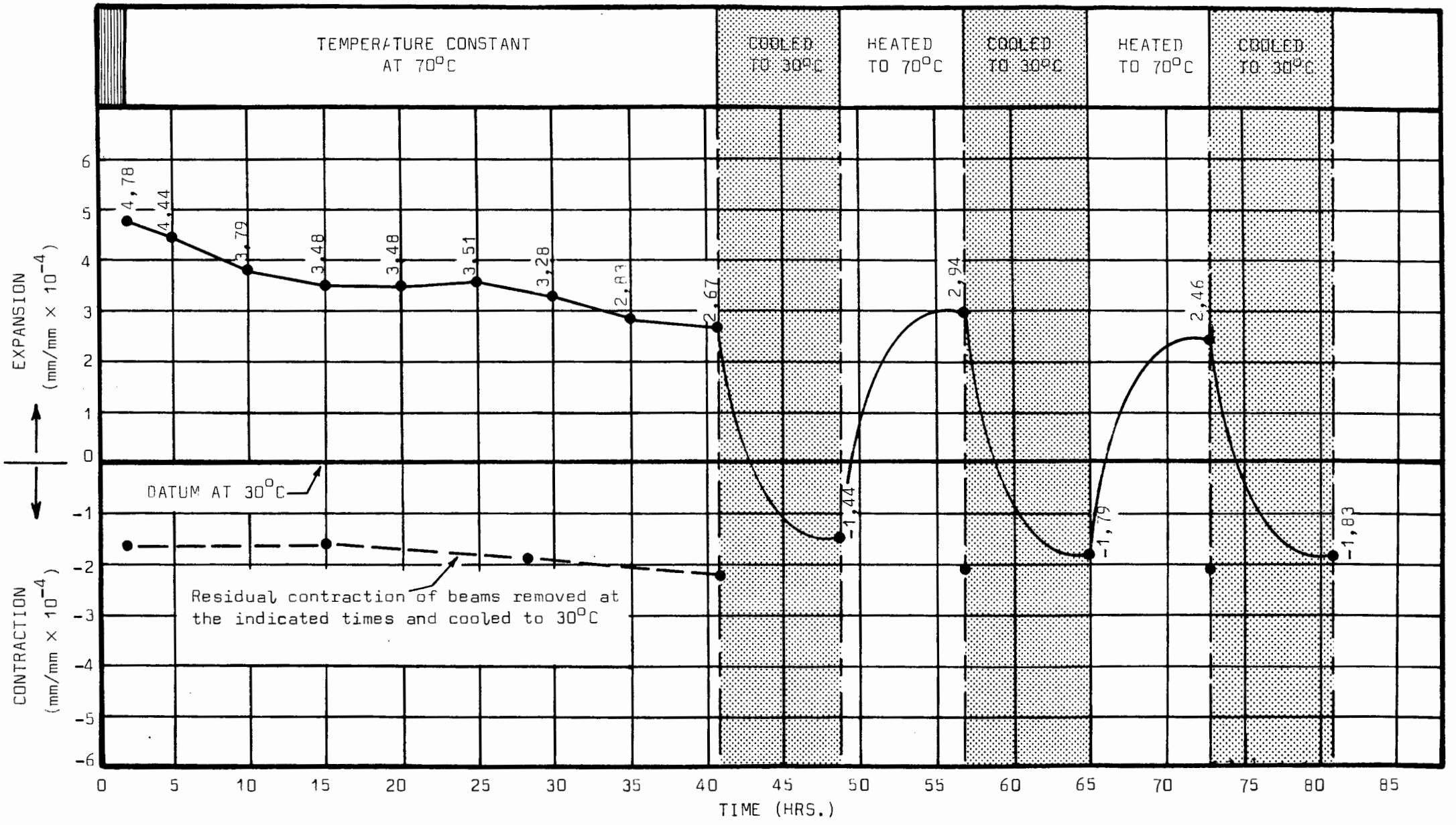


FIG.A.IV.3: The linear deformation of test specimen: Mix BCY at 70°C (dry).

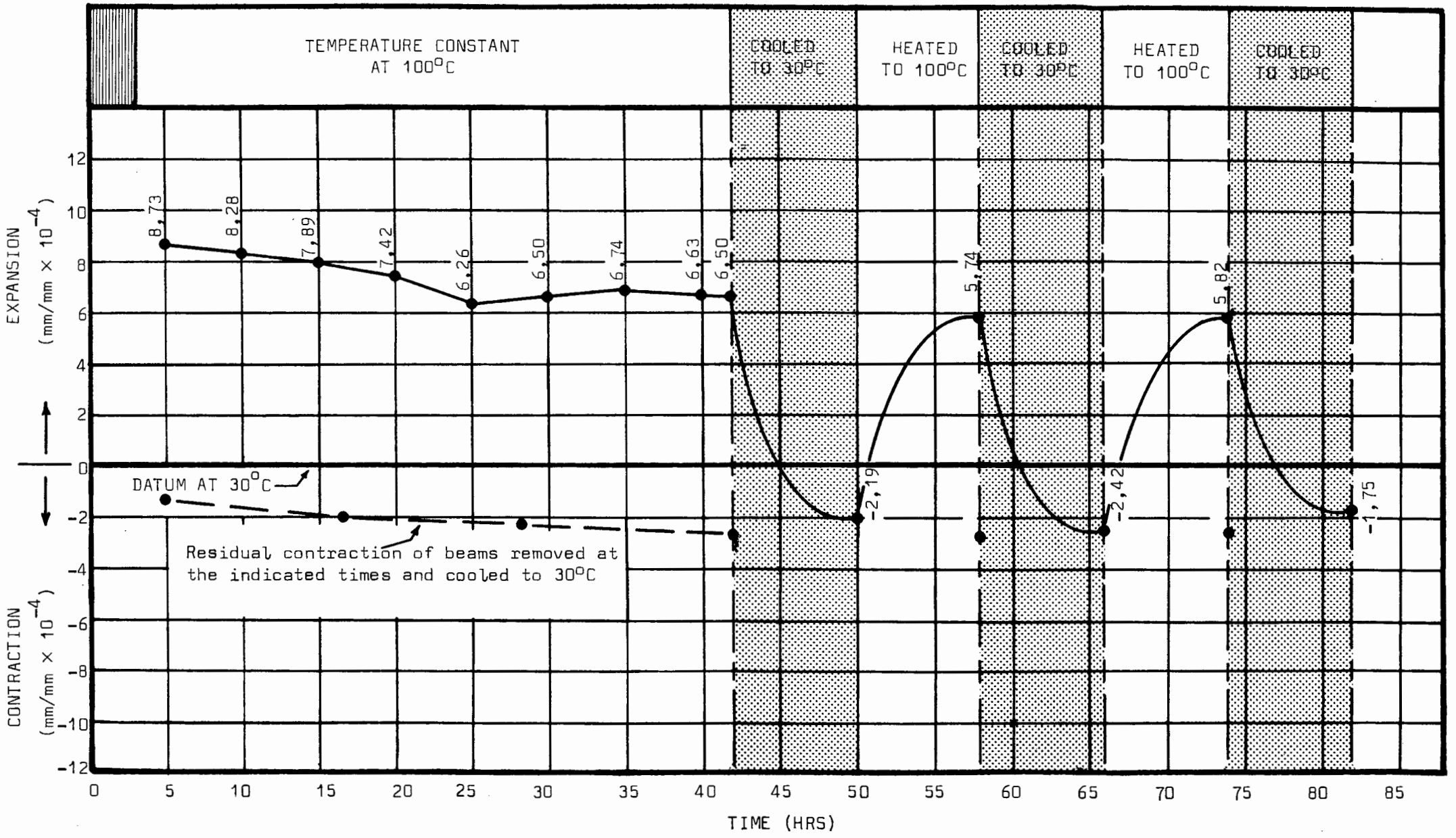


FIG.A.IV.4: The linear deformation of test specimen: Mix BCY at 100°C (dry).

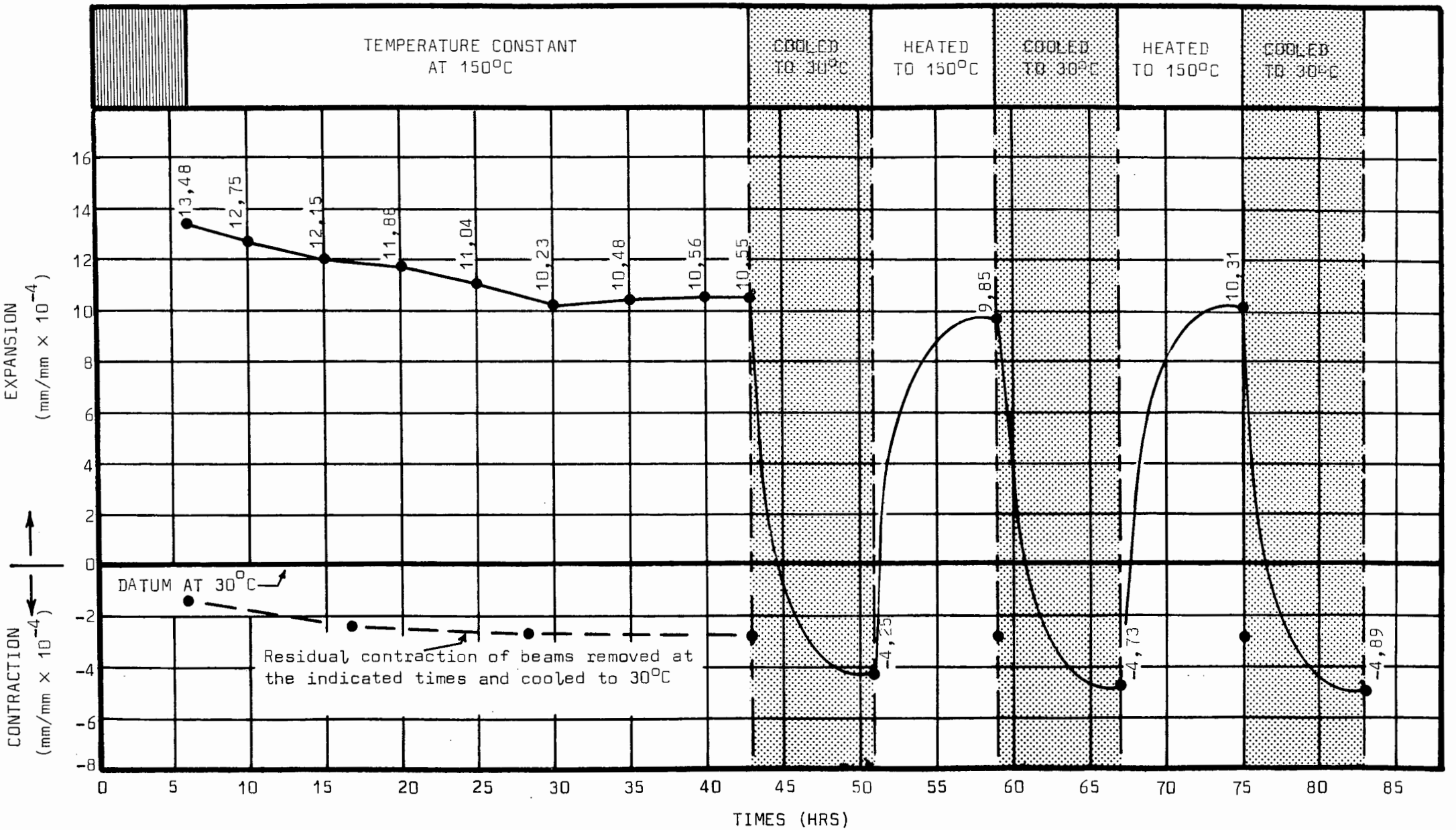


FIG.A.IV.5: The linear deformation of test specimen: Mix BCY at 150°C (dry).

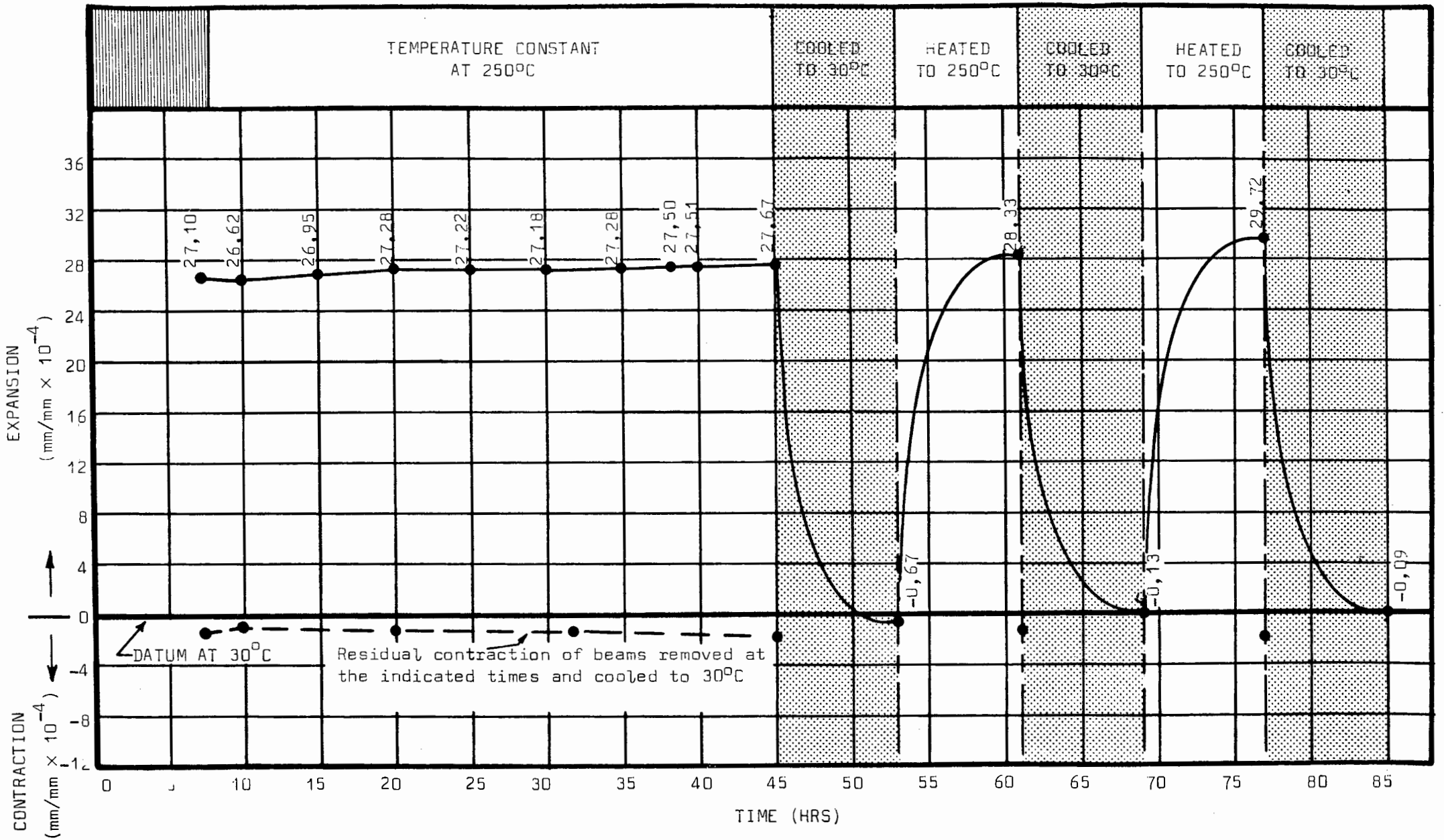


FIG.A.IV.6: The linear deformation of test specimen: Mix BCY at 250°C (dry).

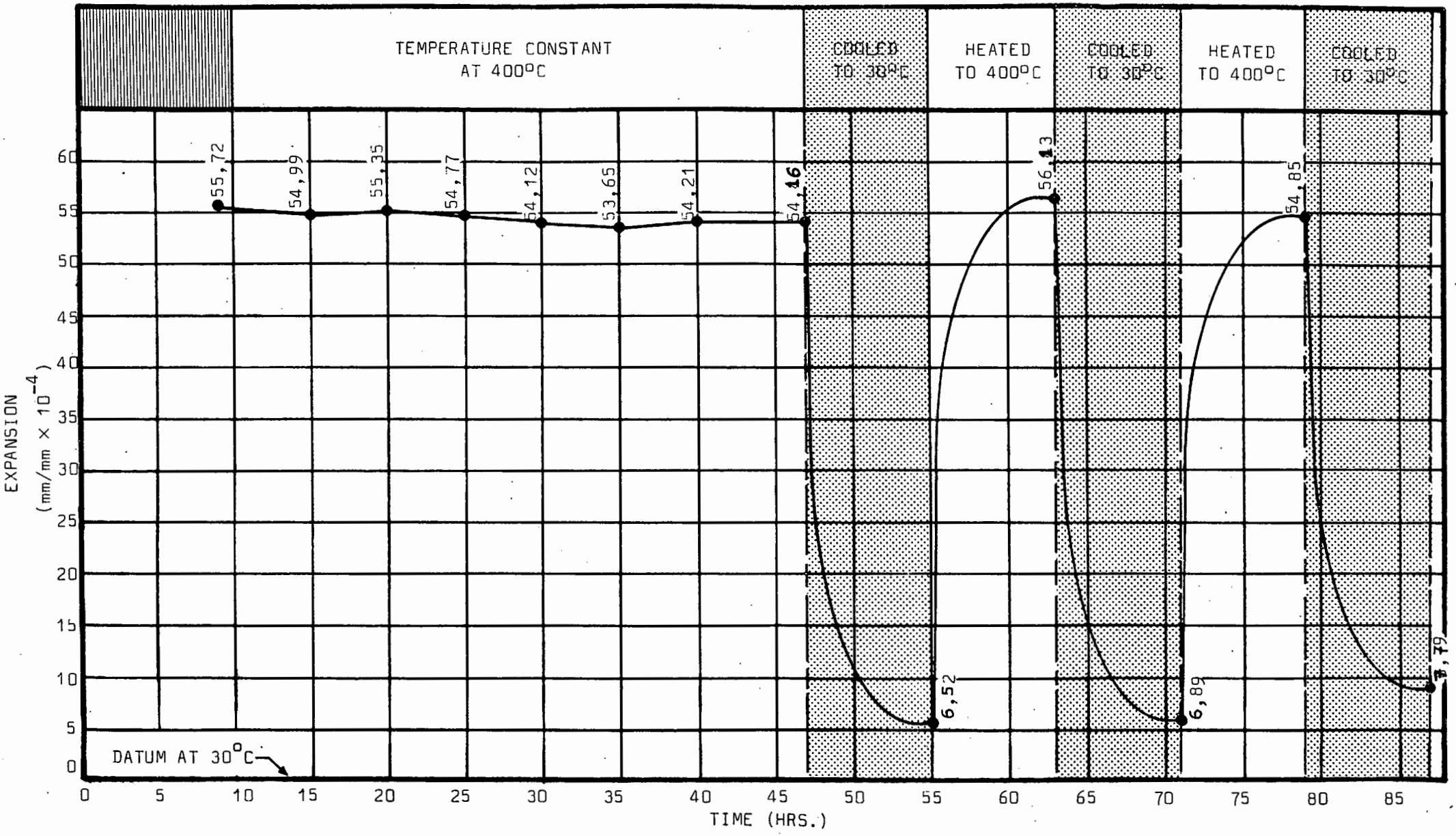


FIG.A.IV.7: The linear deformation of test specimen: Mix BCY at 400°C (dry).

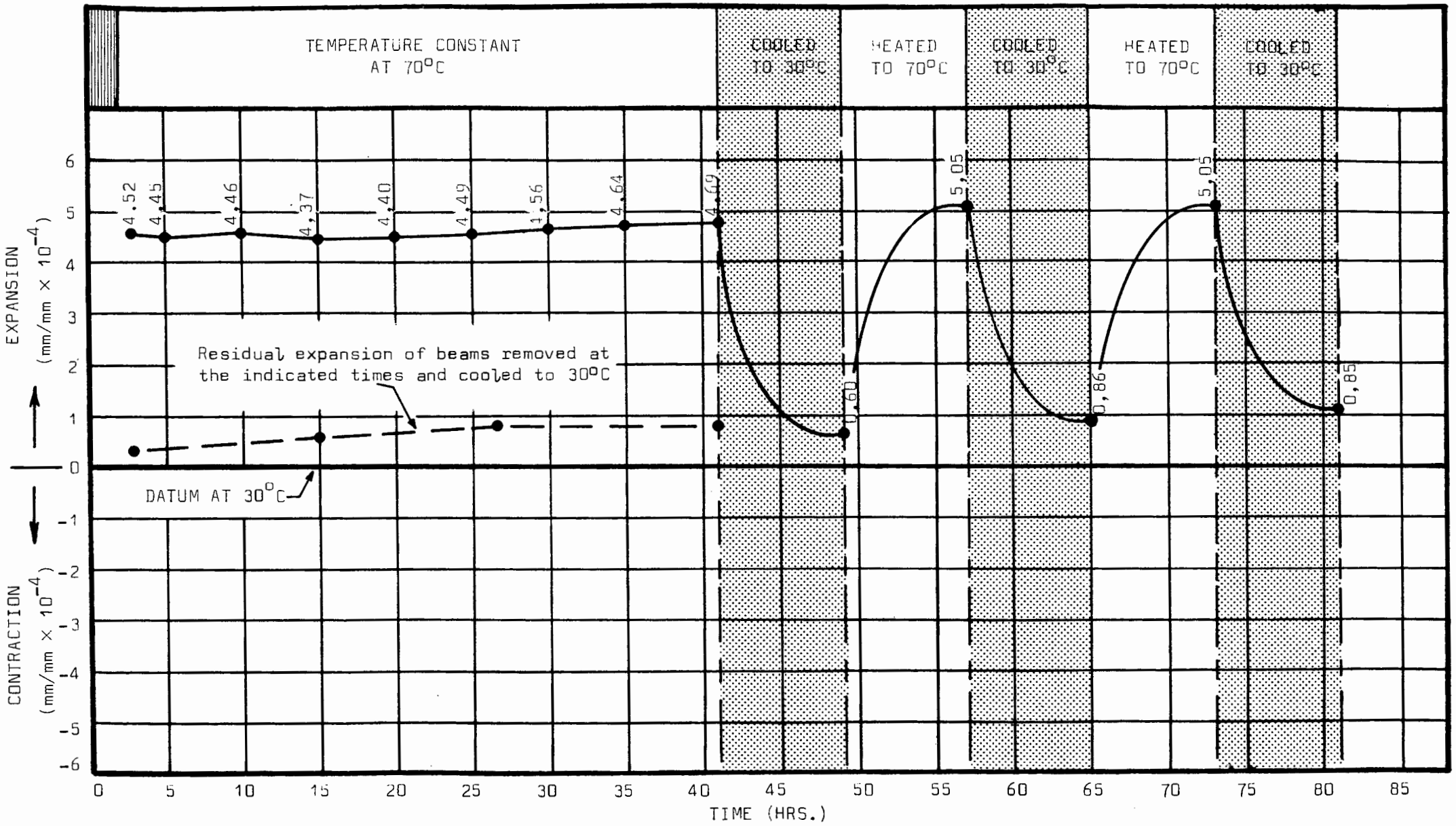


FIG.A.IV.8: The linear deformation of test specimen: Mix CCX at 70°C (saturated).

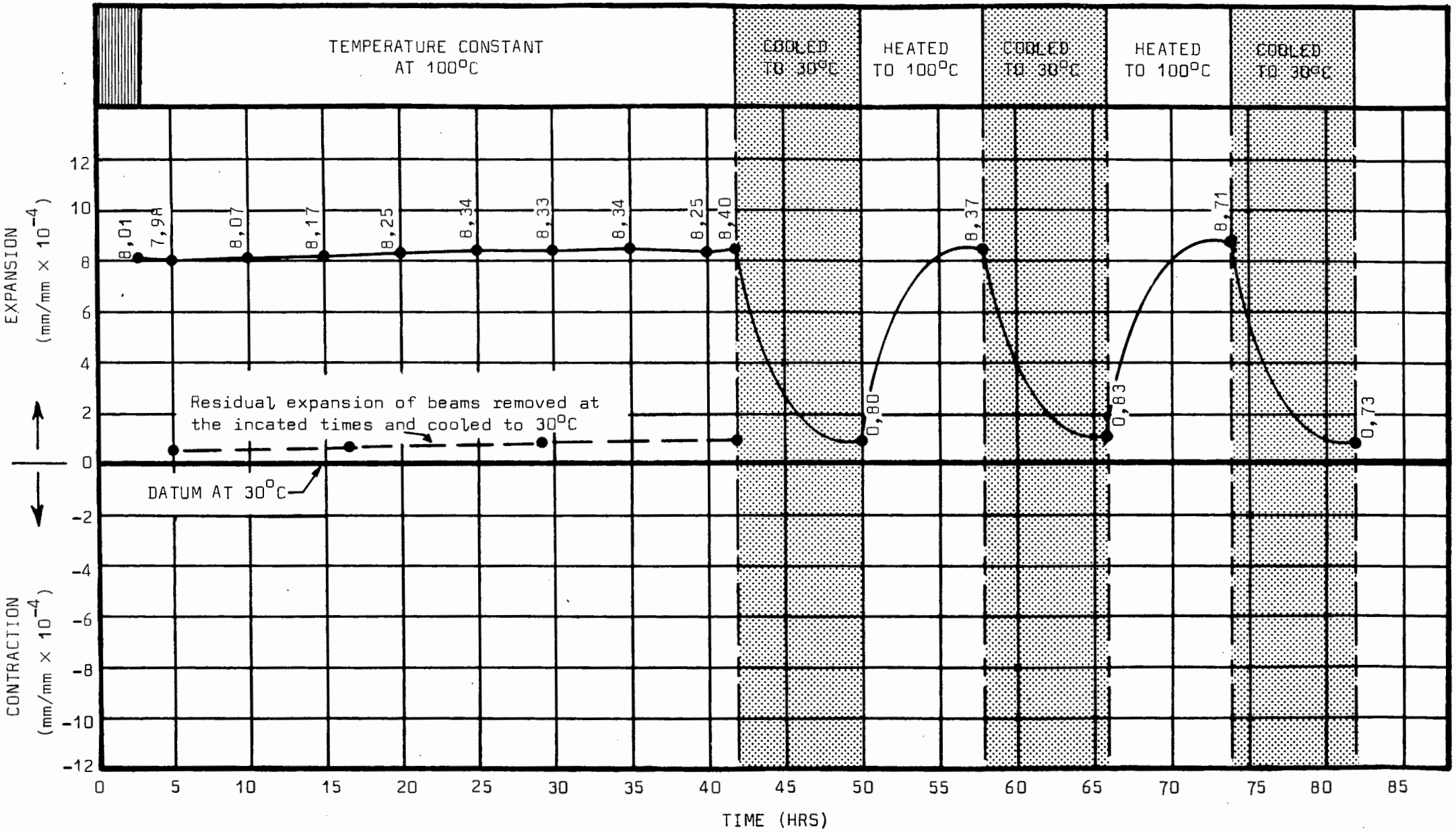


FIG.A.IV.9: The linear deformation of test specimen: Mix CCX at 100°C (saturated).

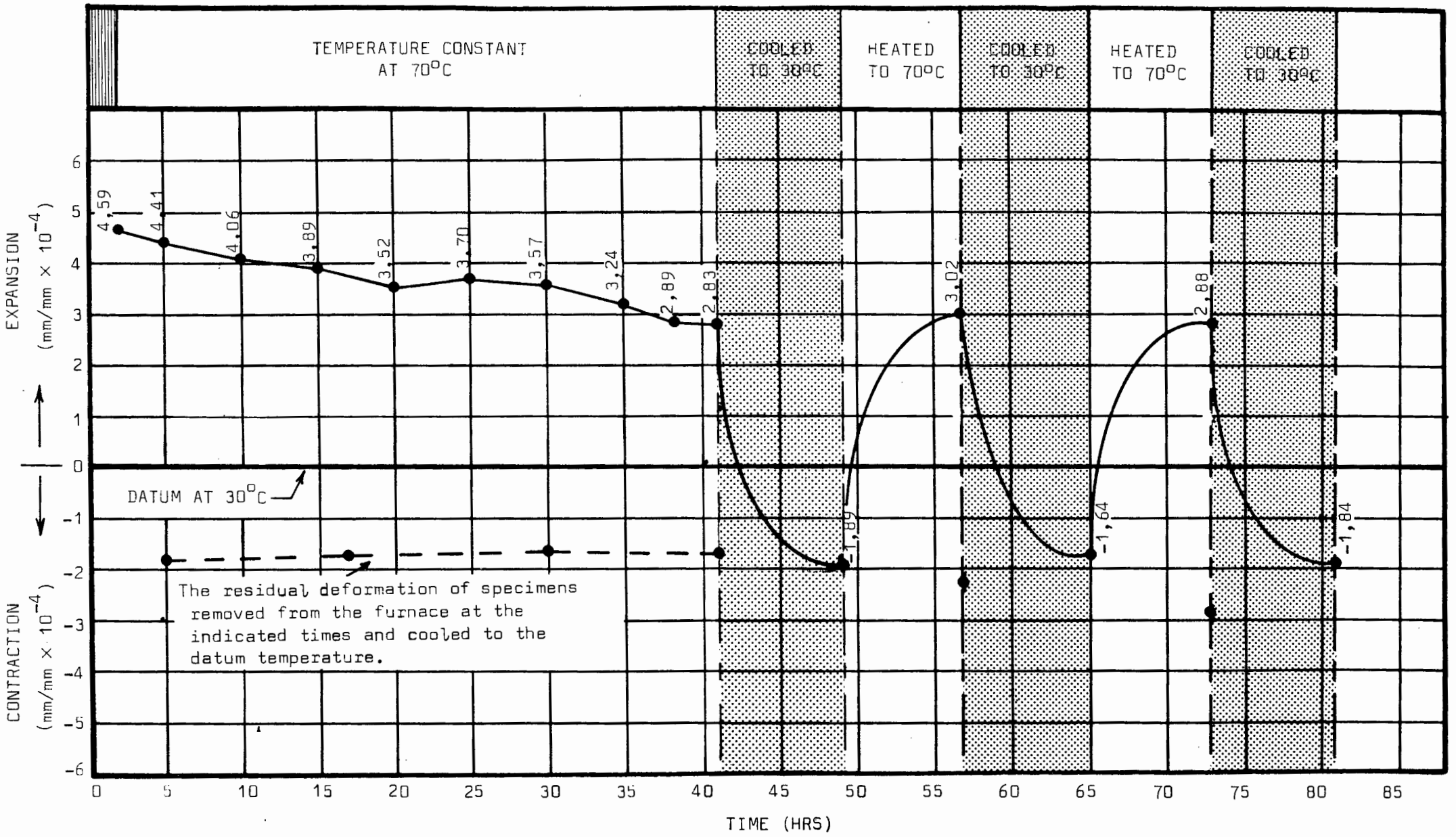


FIG.A.IV.10: The linear deformation of test specimen: Mix CCX at 70°C (dry).

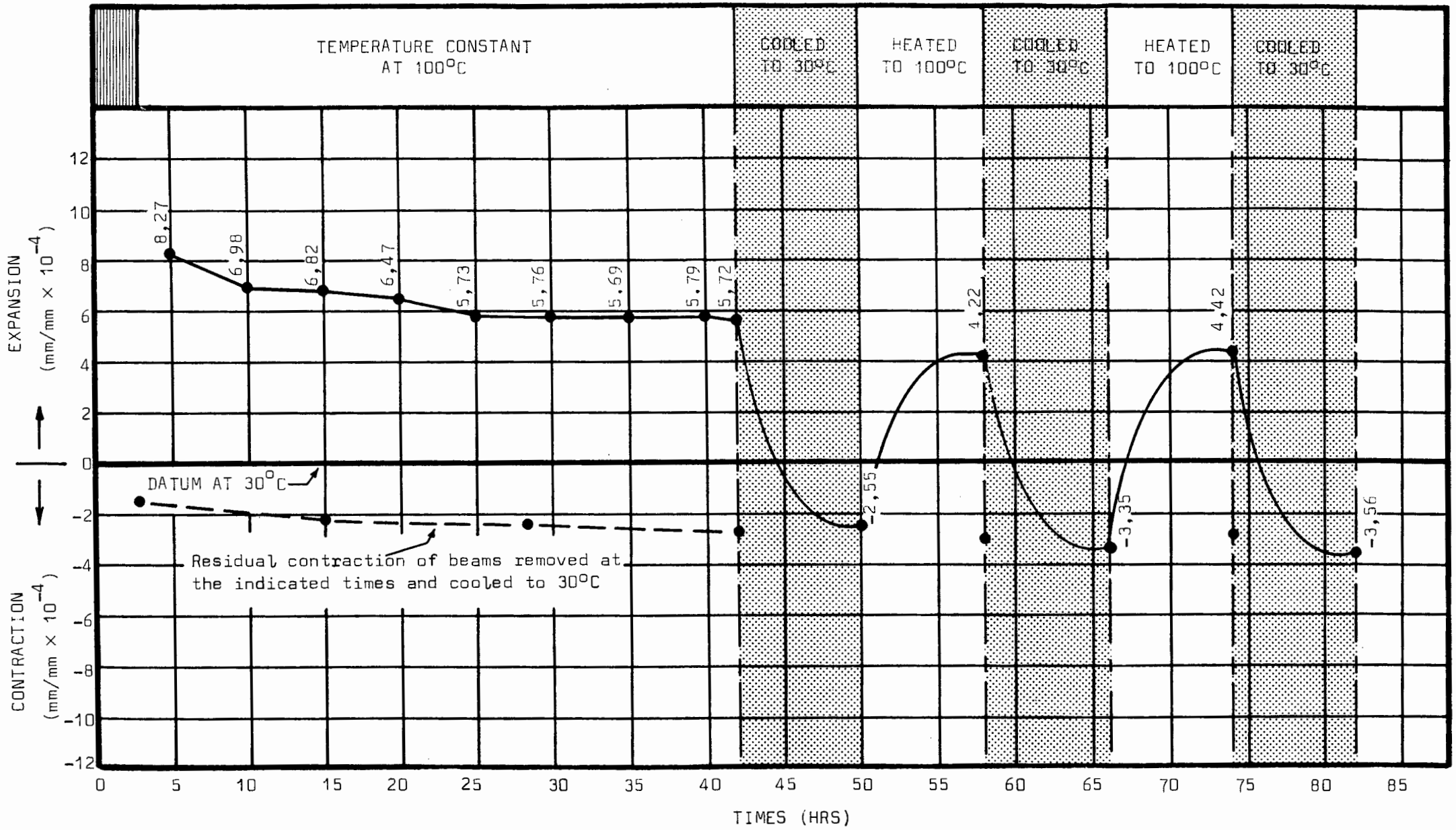


FIG.A.IV.11: The linear deformation of test specimen: Mix CCX at 100°C (dry).

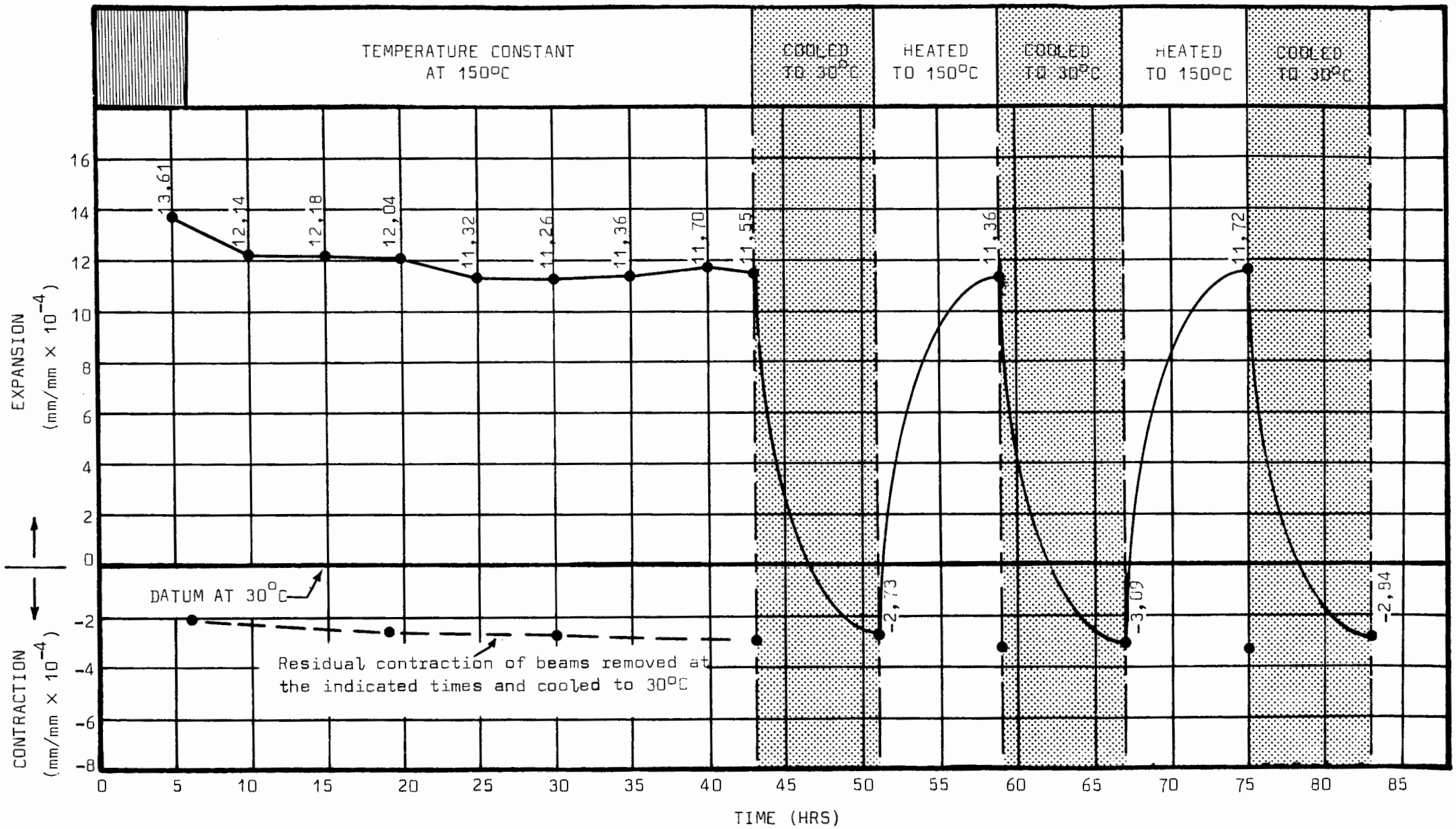


FIG.A.IV.12: The linear deformation of test specimen: Mix CCX at 150°C (dry).

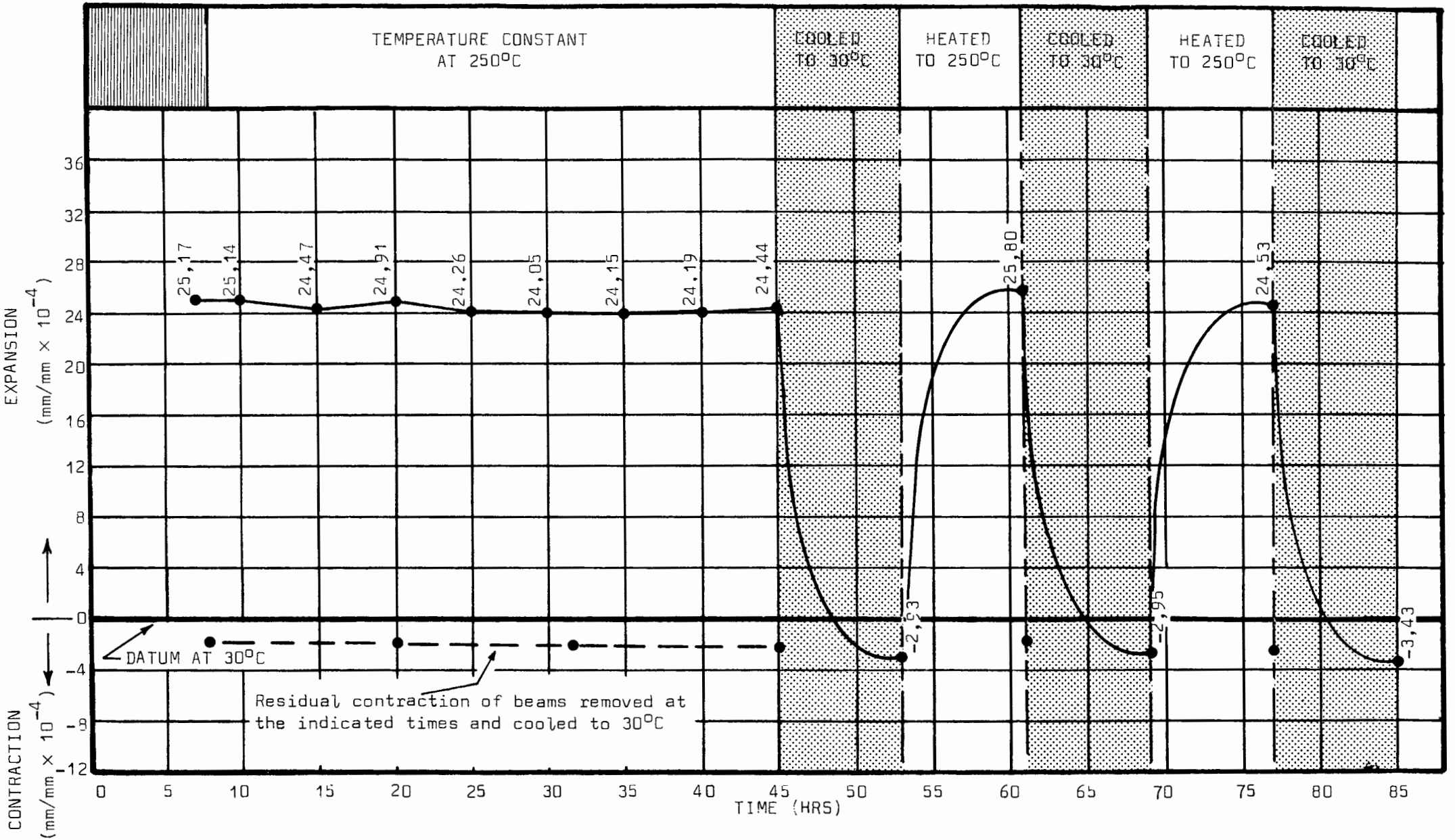


FIG.A.IV.13: The linear deformation of test specimen: Mix CCX at 250°C (dry).

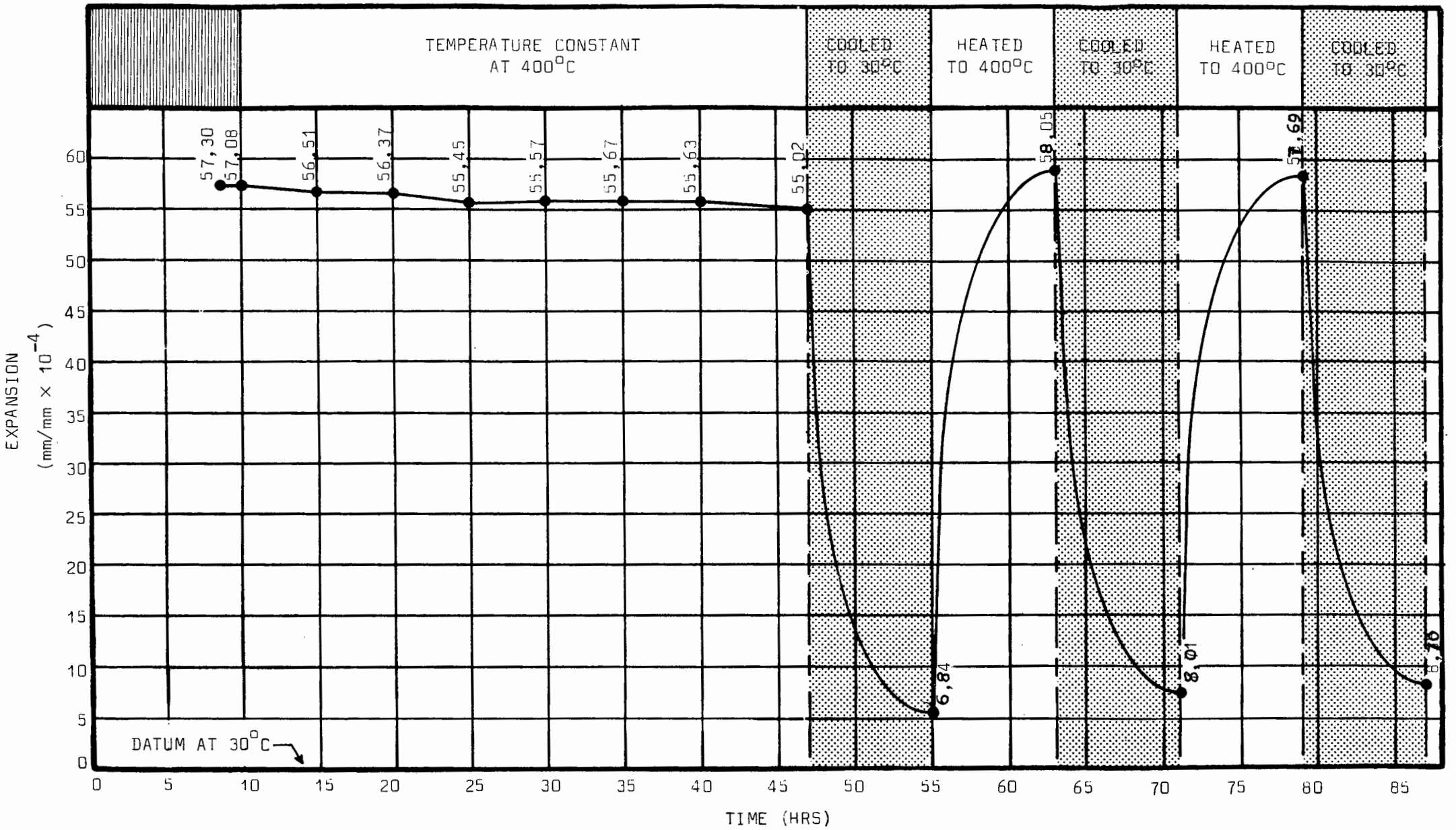


FIG.A.IV.14: The linear deformation of test specimen: Mix CCX at 400°C (dry).

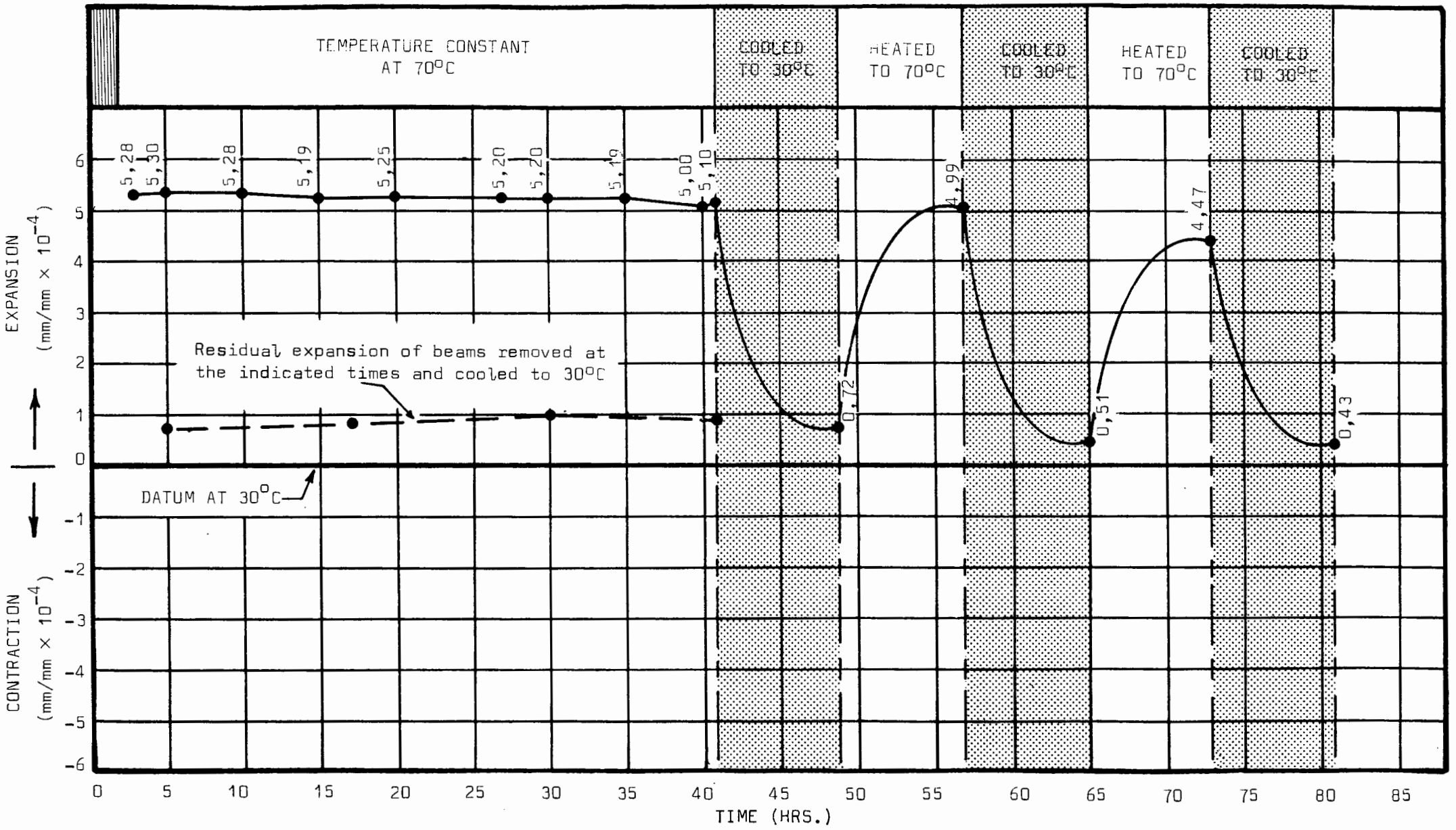


FIG.A.IV.15: The linear deformation of test specimen: Mix CCY at 70°C (saturated).

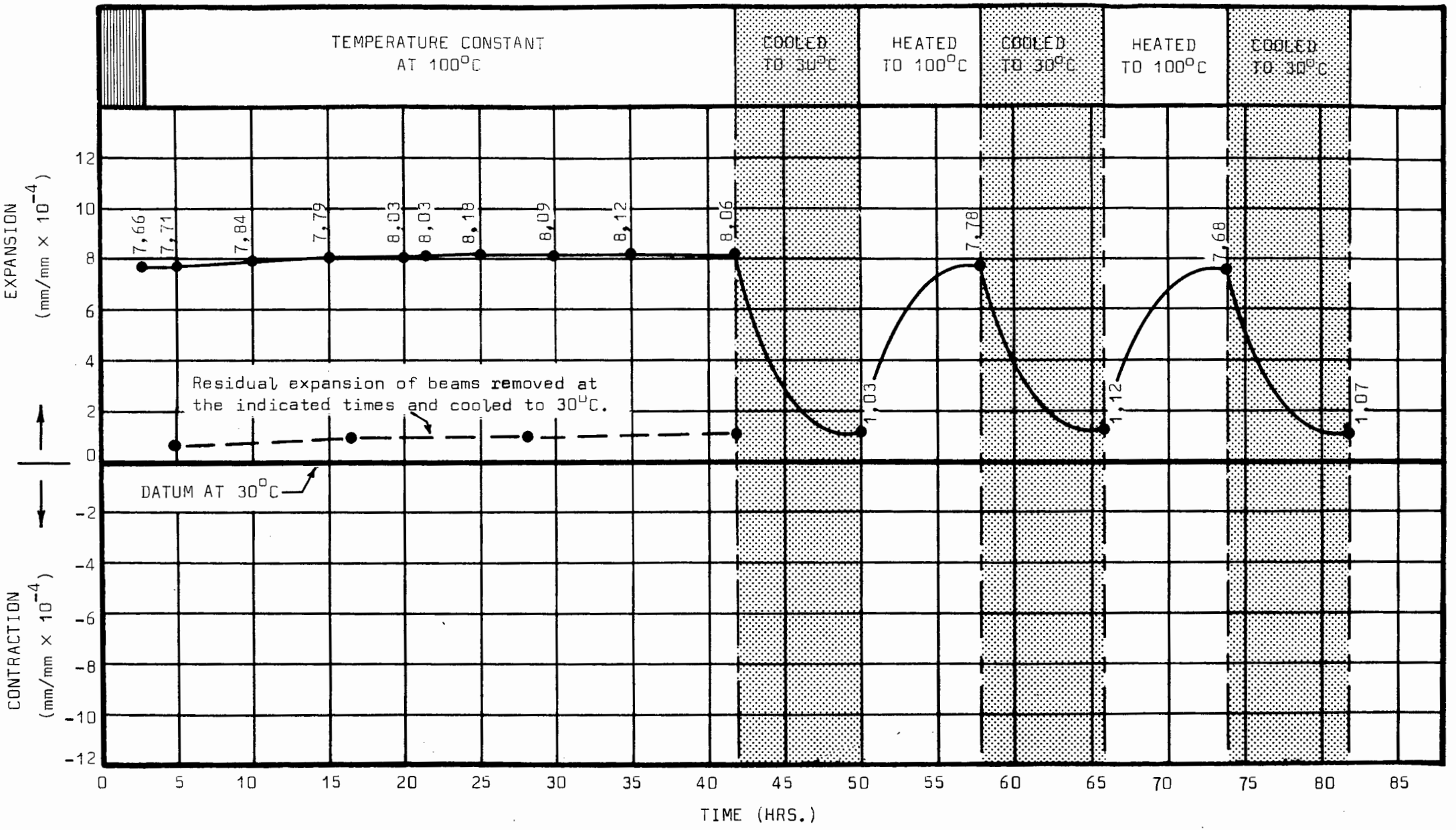


FIG.A.IV.16: The linear deformation of test specimen: Mix CCY at 100°C (saturated).

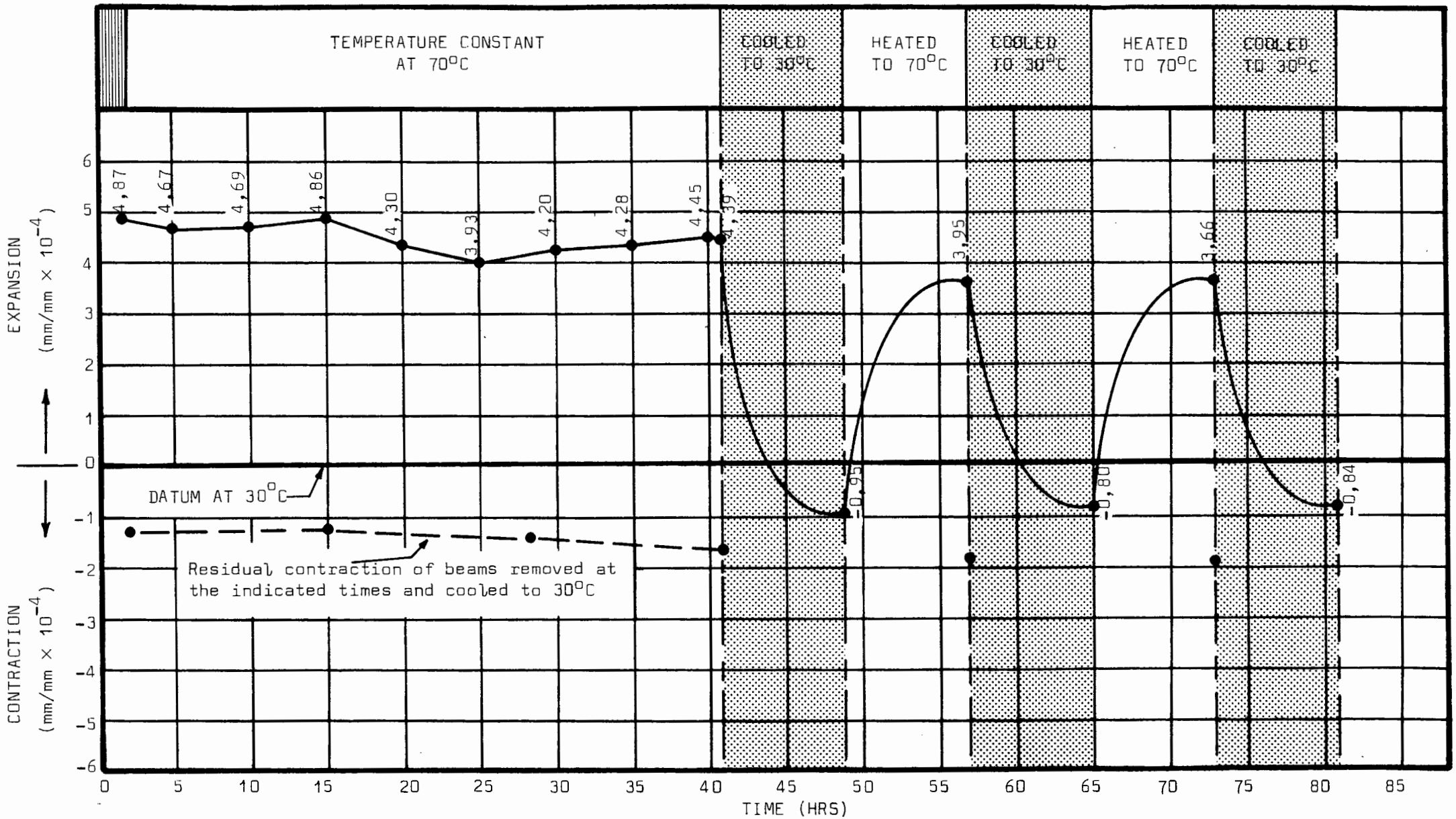


FIG.A.IV.17: The linear deformation of test specimen: Mix CCY at 70°C (dry).

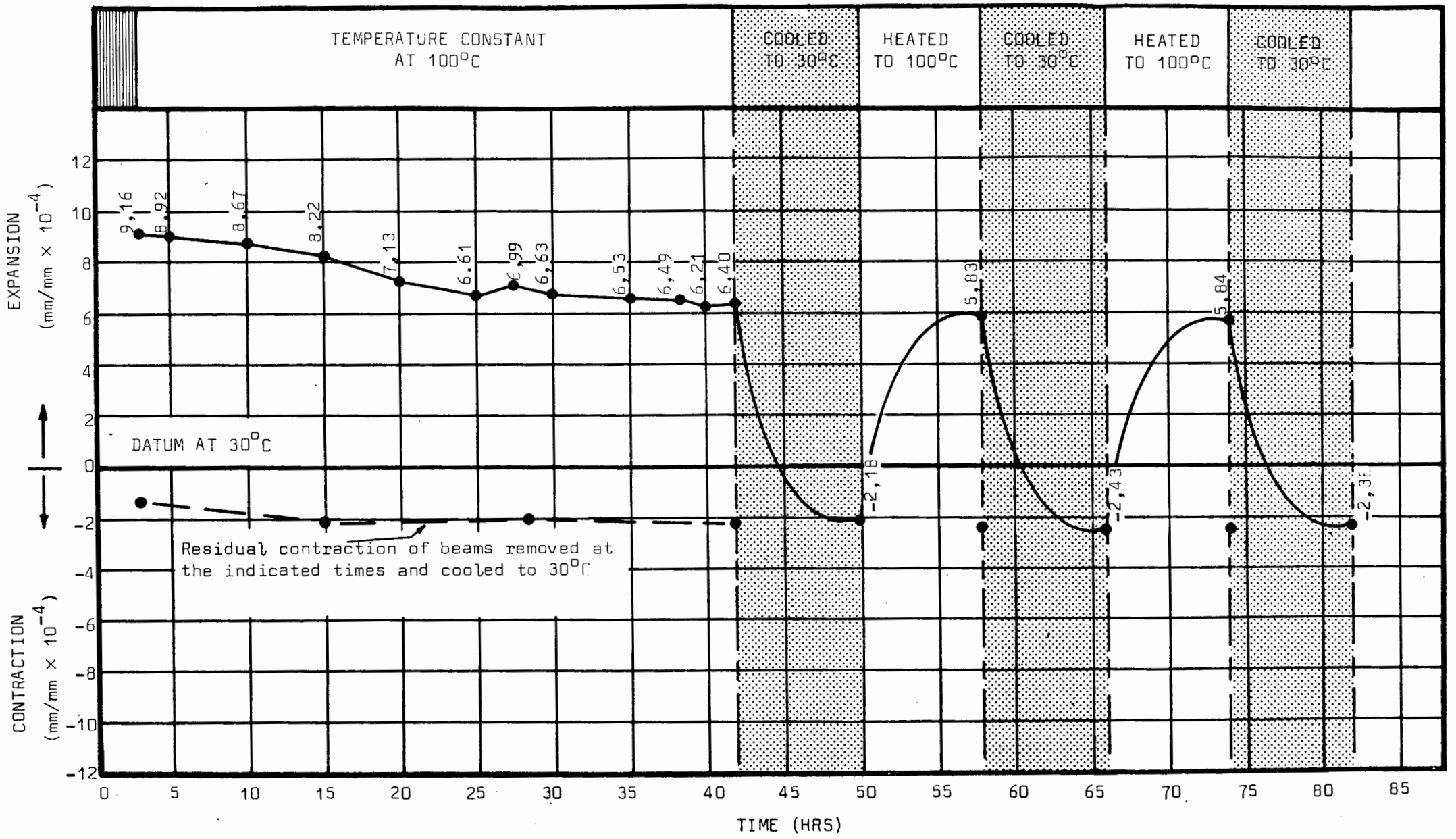


FIG.A.IV.18: The linear deformation of test specimen: Mix CCY at 100°C (dry).

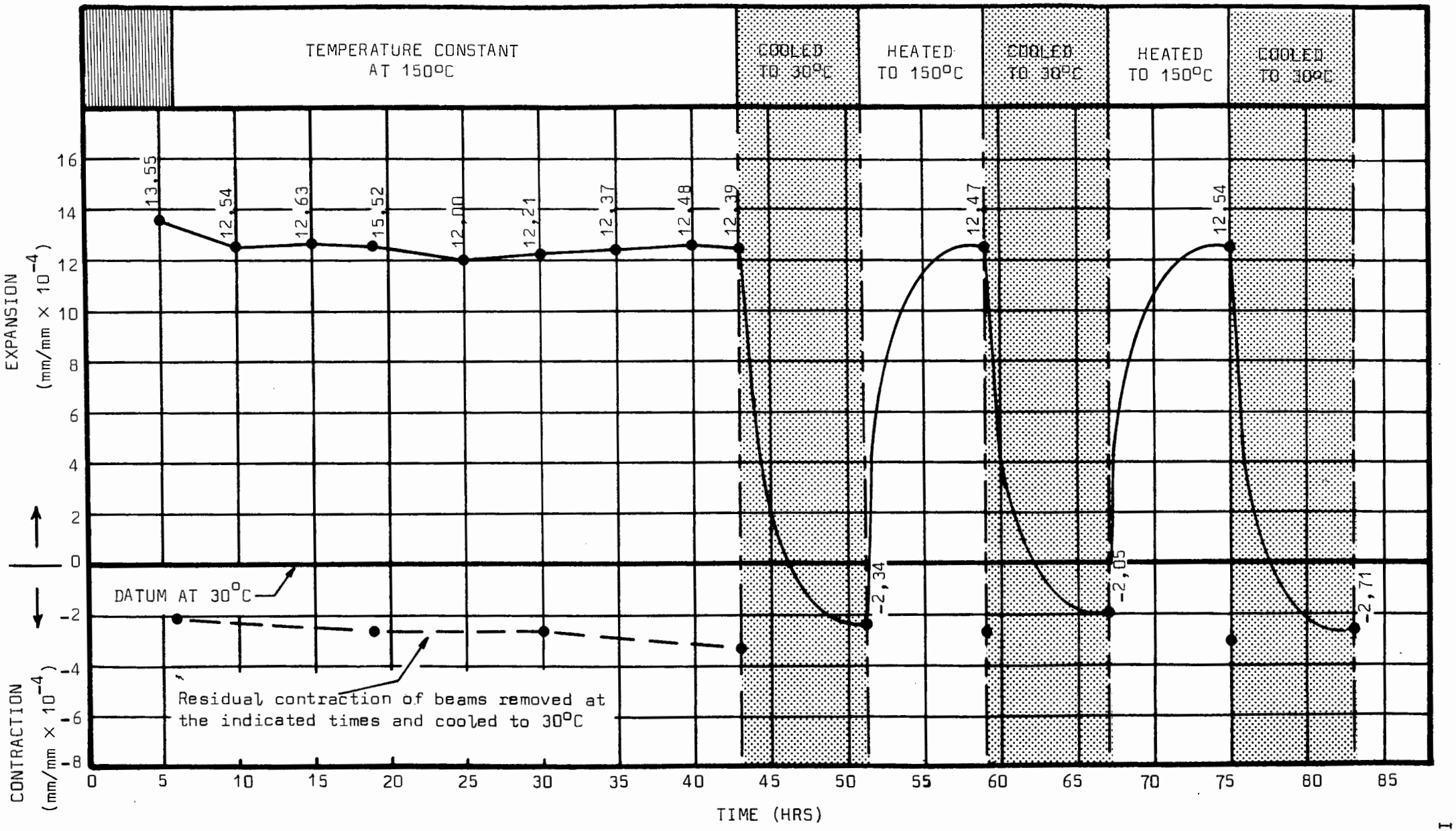


FIG.A.IV.19: The linear deformation of test specimen: Mix CCY at 150°C (dry).

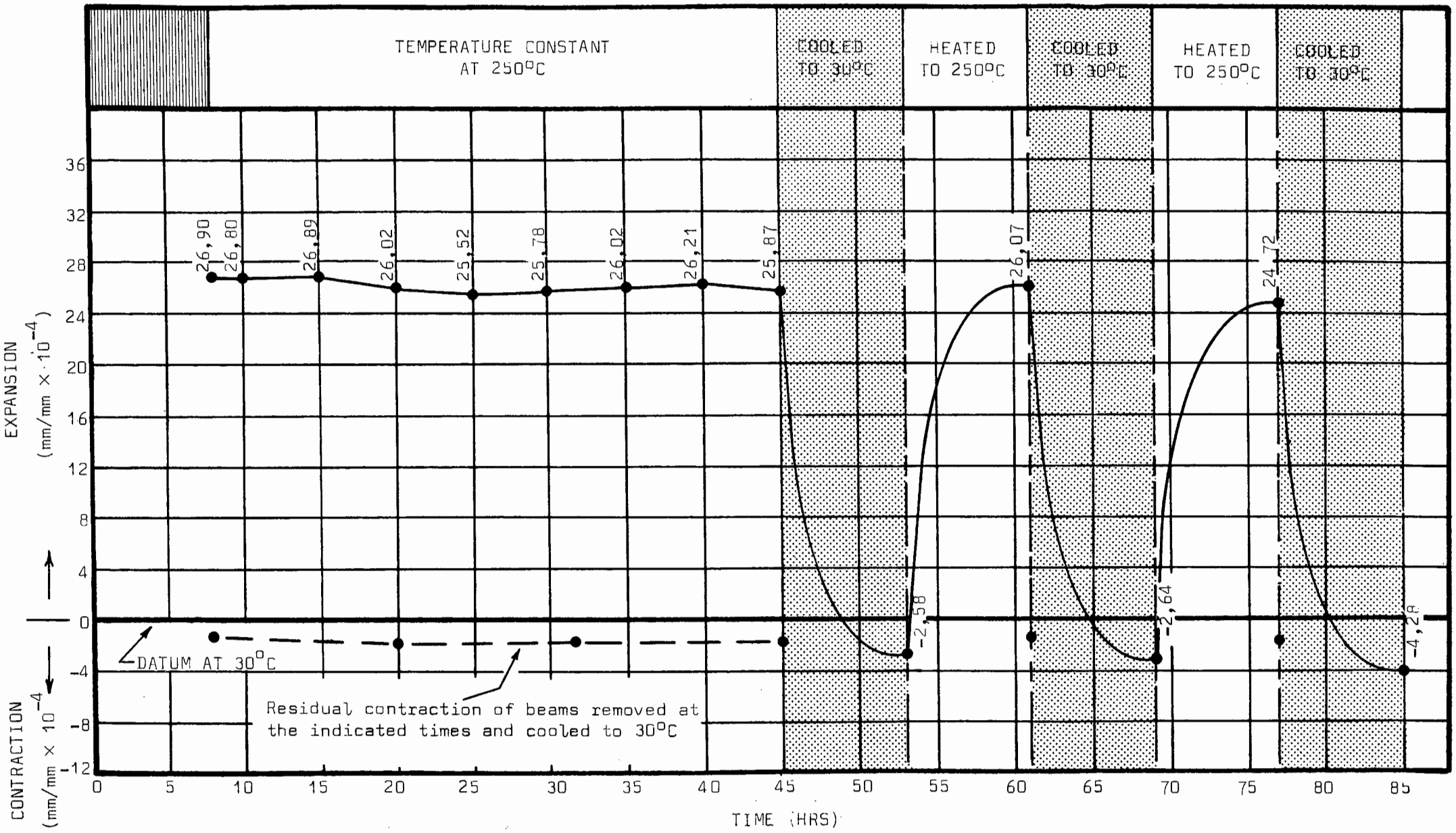


FIG.A.IV.20: The linear deformation of test specimen: Mix CCY at 250°C (dry).

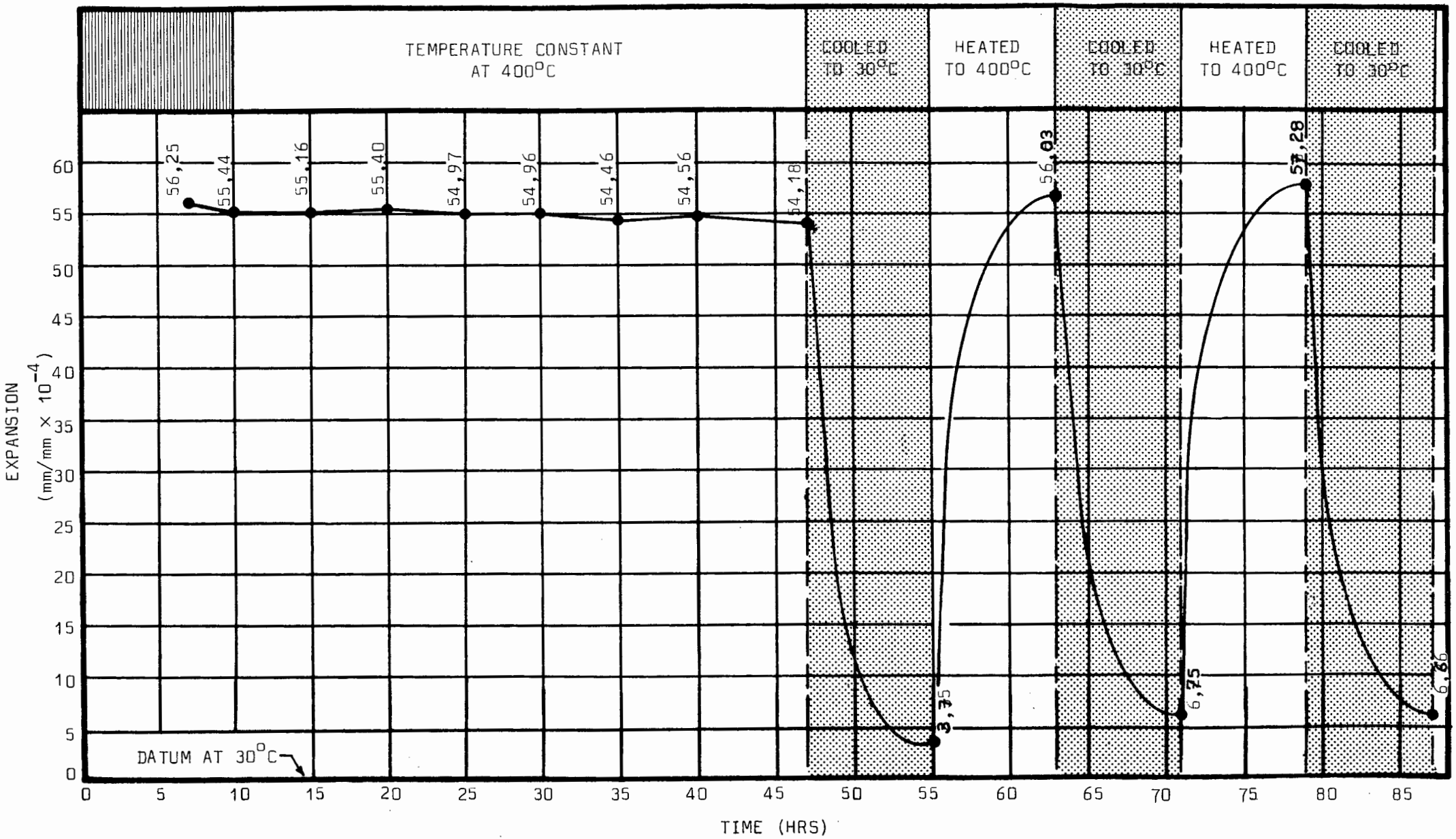


FIG.A.IV.21: The linear deformation of test specimen: Mix CCY at 400°C (dry).

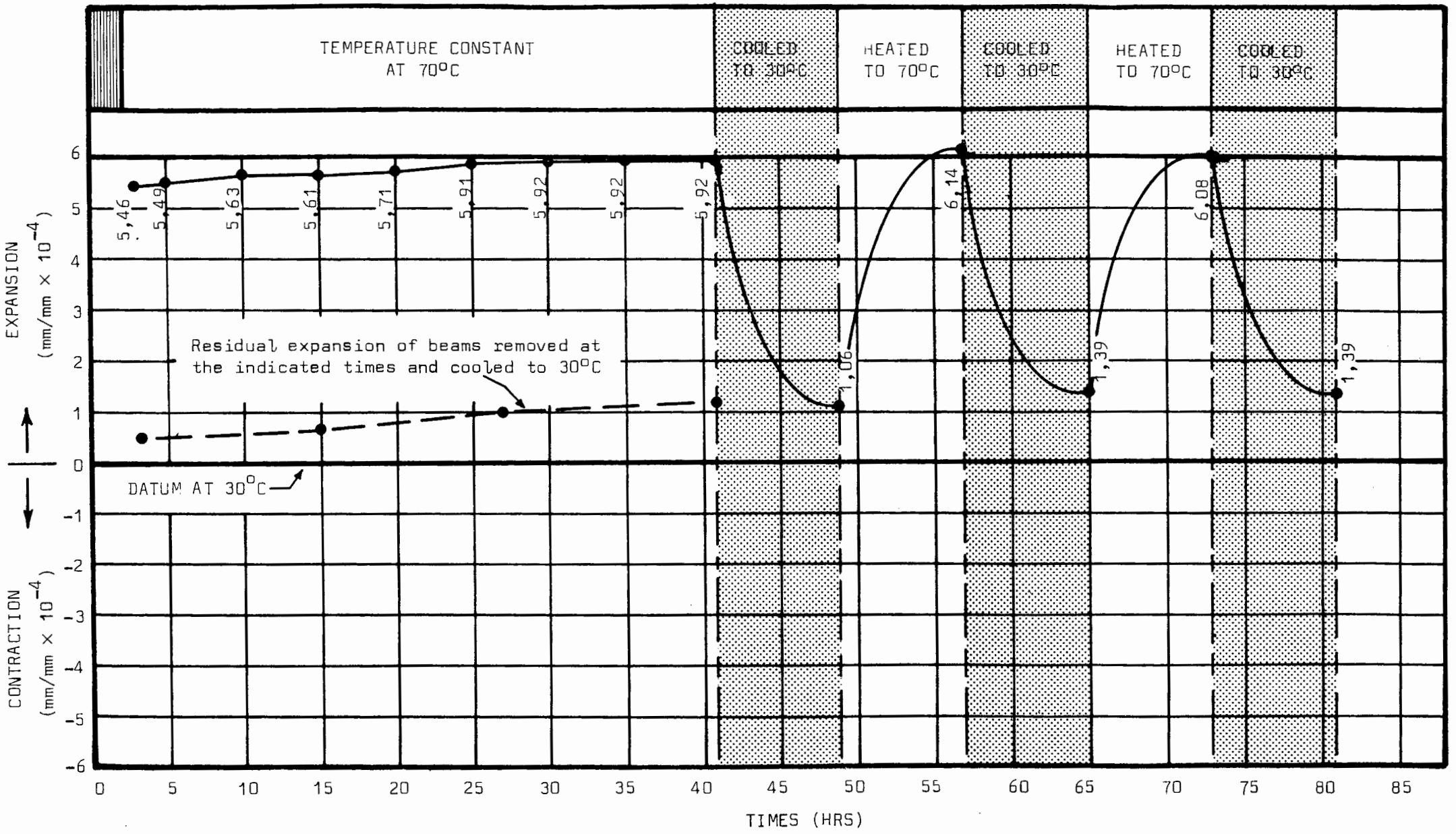


FIG.A.IV.22: The linear deformation of test specimen: Mix BMY at 70°C (saturated).

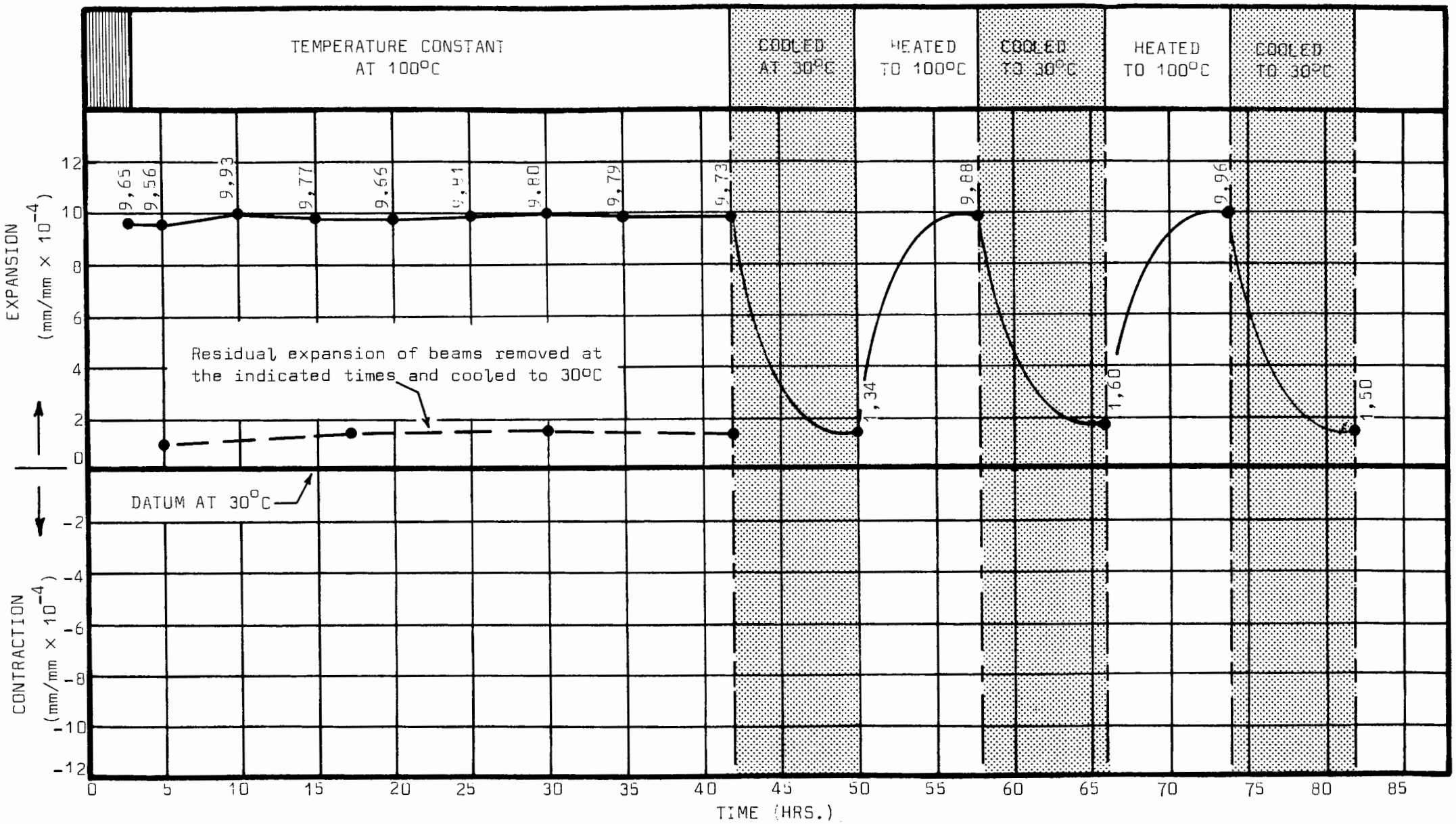


FIG.A.IV.23: The linear deformation of test specimen: Mix BMY at 100°C (saturated).

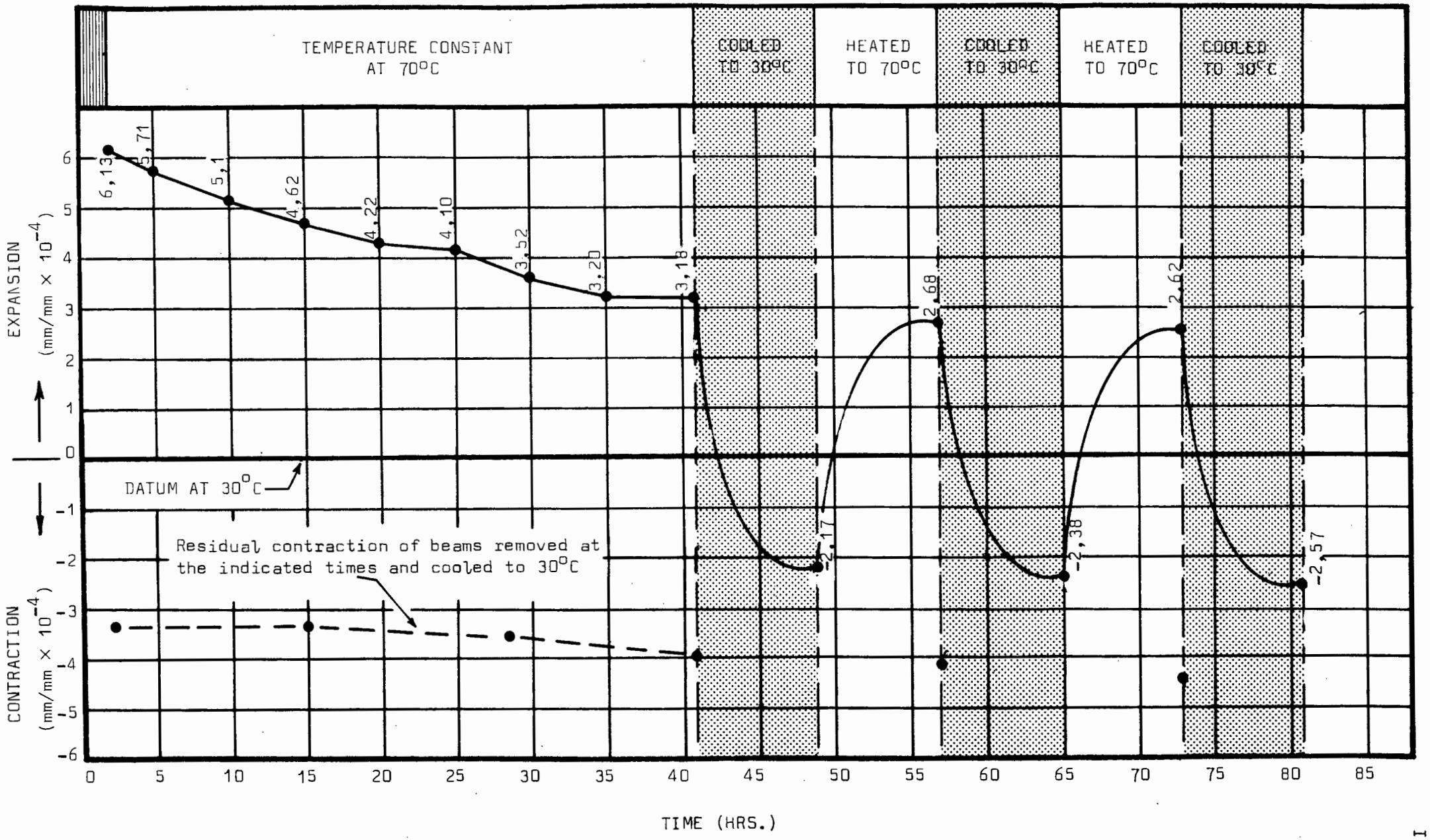


FIG.A.IV.24: The linear deformation of test specimen: Mix BMY at 70°C (dry).

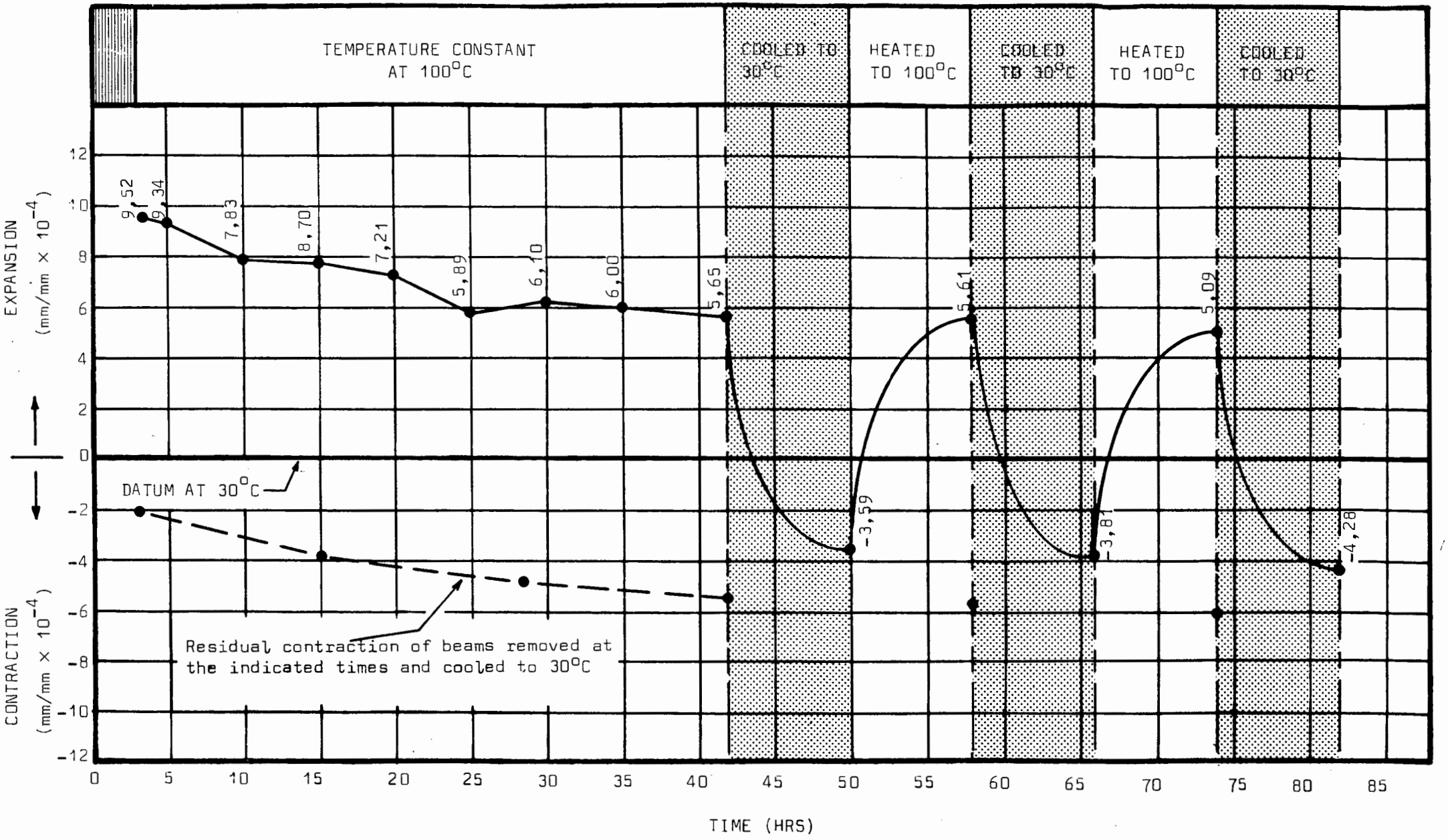


FIG.A.IV.25: The linear deformation of the test specimen: Mix BMY at 100°C (dry).

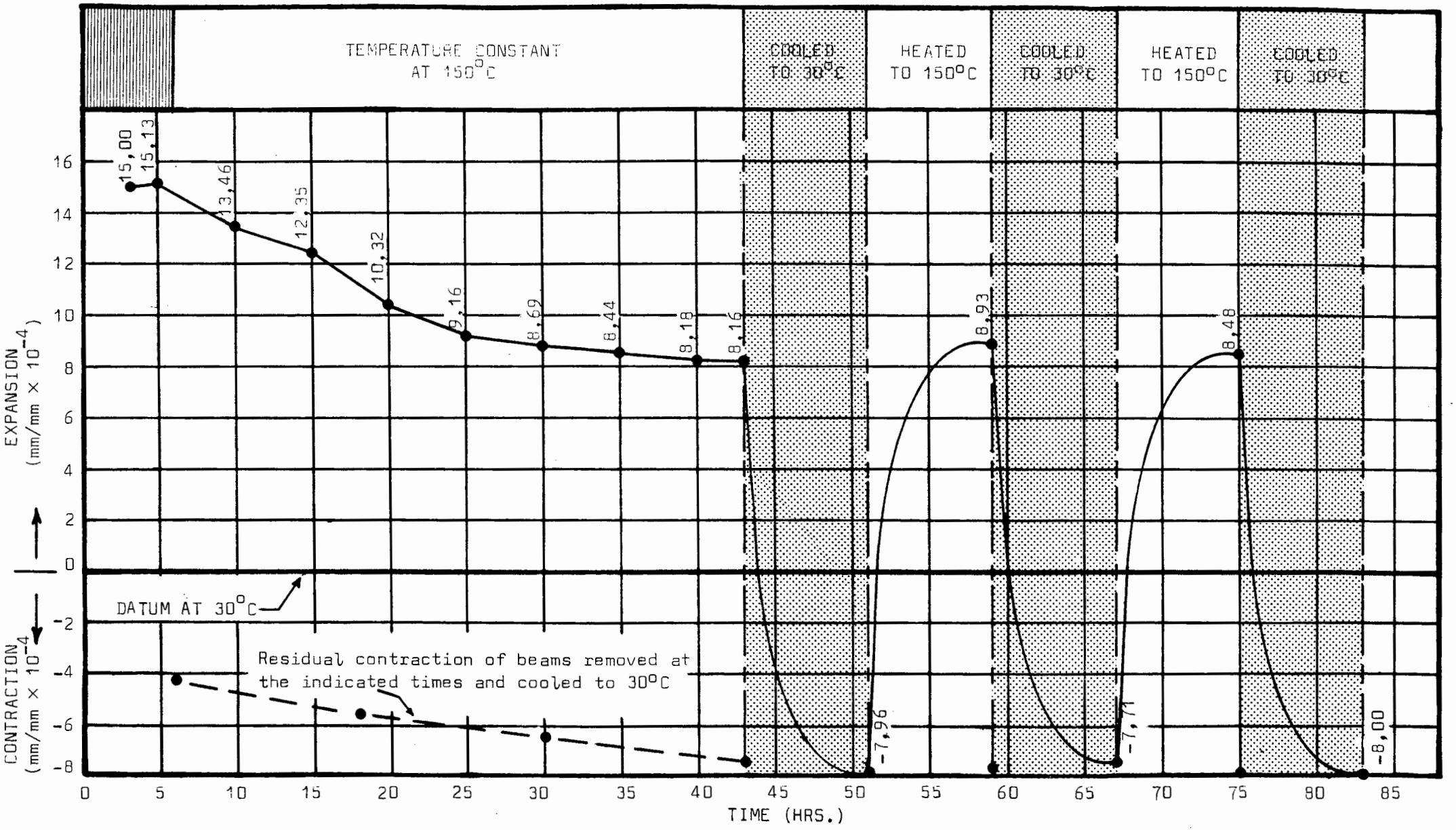


FIG.A.IV.26: The linear deformation of test specimen: Mix BMY at 150°C (dry).

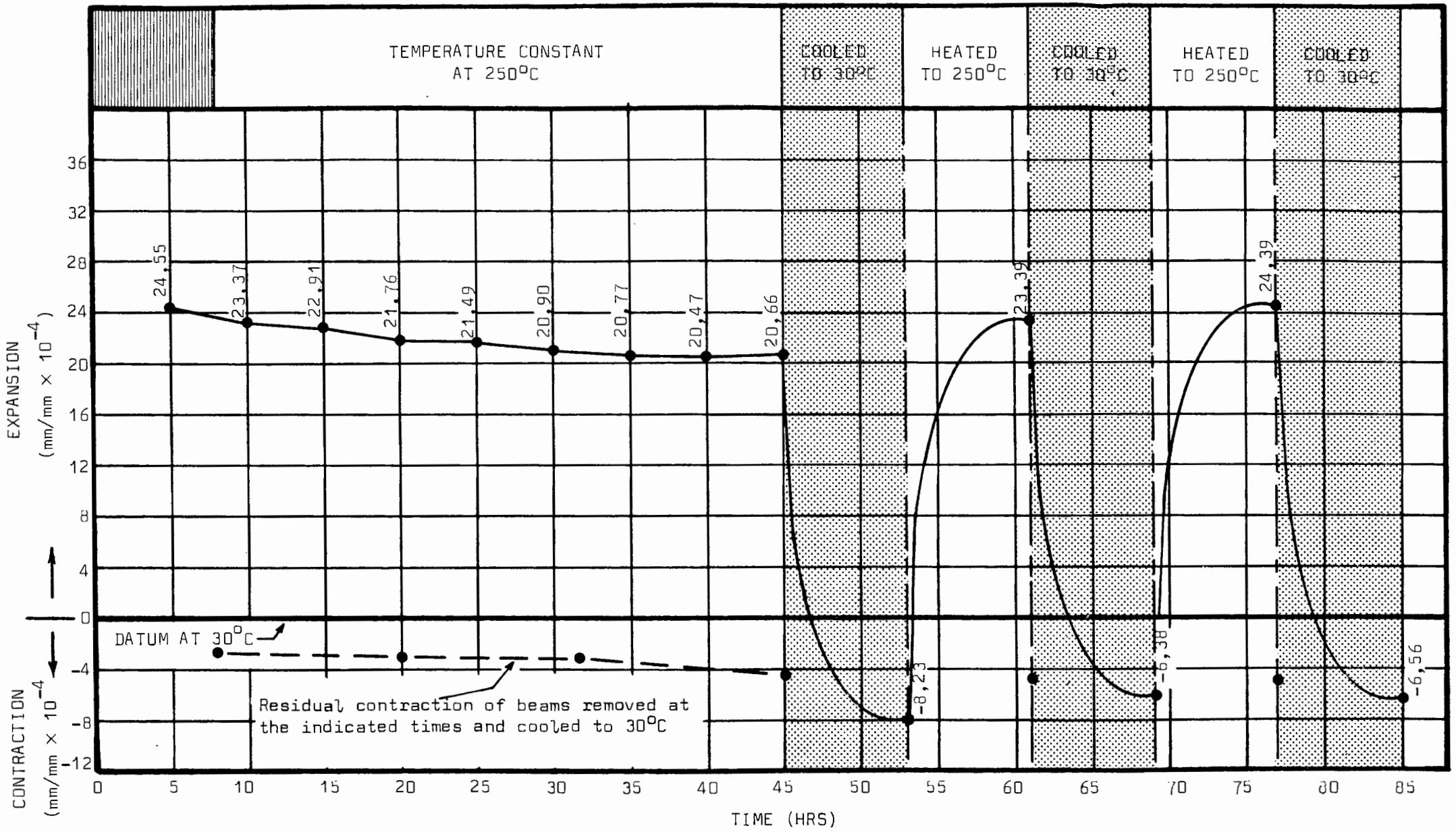


FIG.A.IV.27: The linear deformation of test specimen: Mix BMY at 250°C (dry).

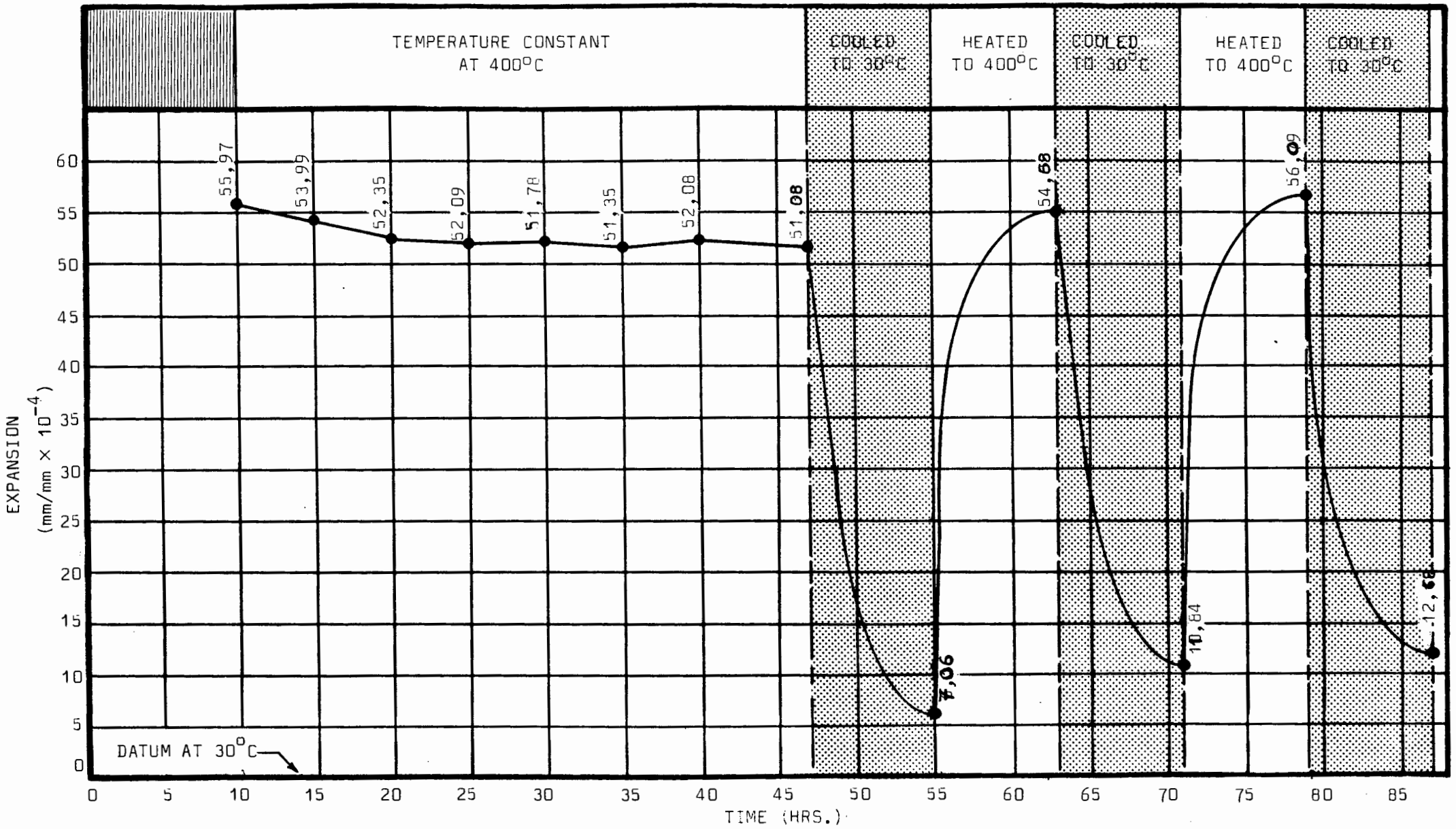


FIG.A.IV.28: The linear deformation of test specimen: Mix BMY at 400°C (dry).

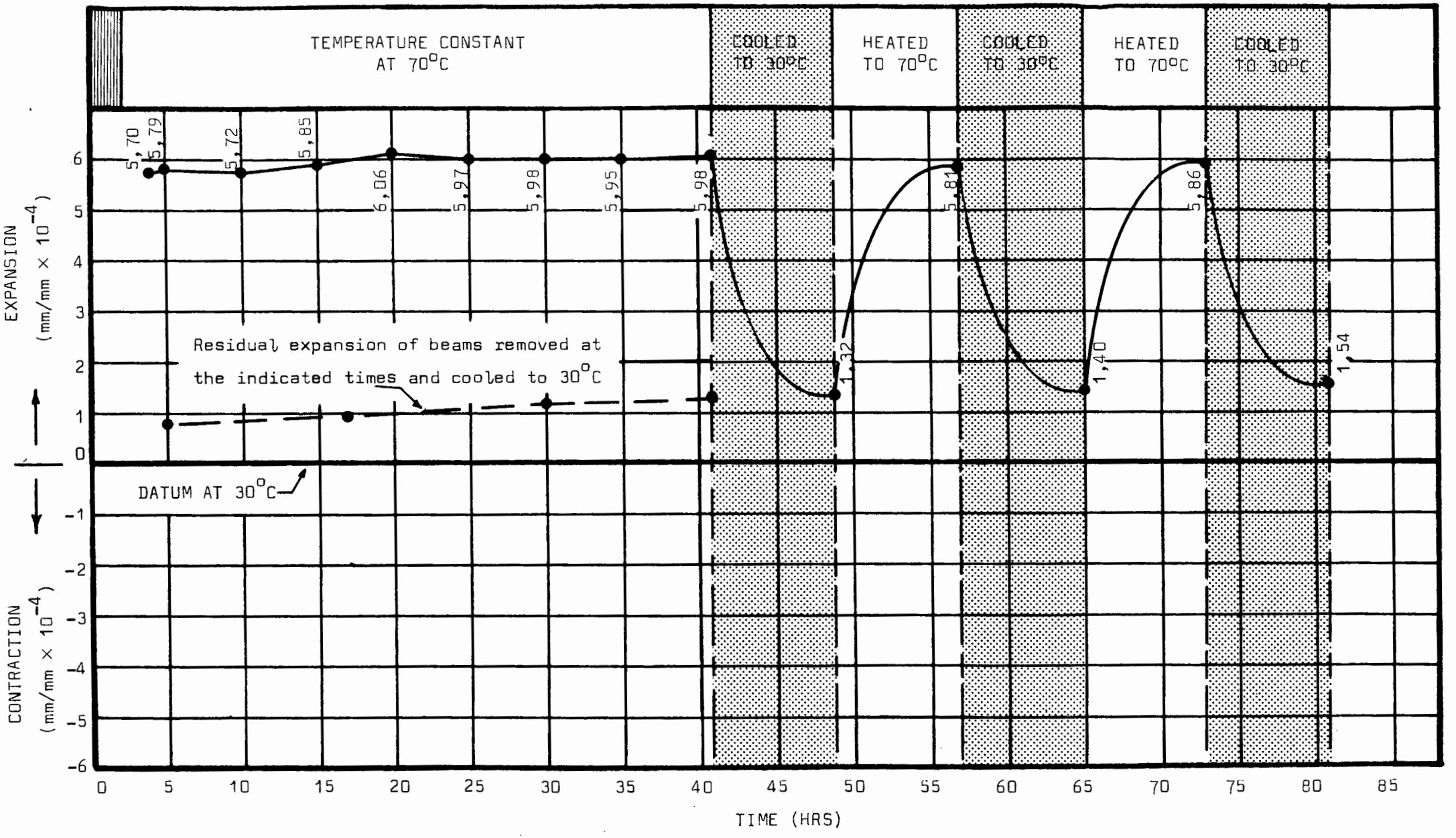


FIG.A.IV.29: The linear deformation of test specimen: Mix CMX at 70°C (saturated).

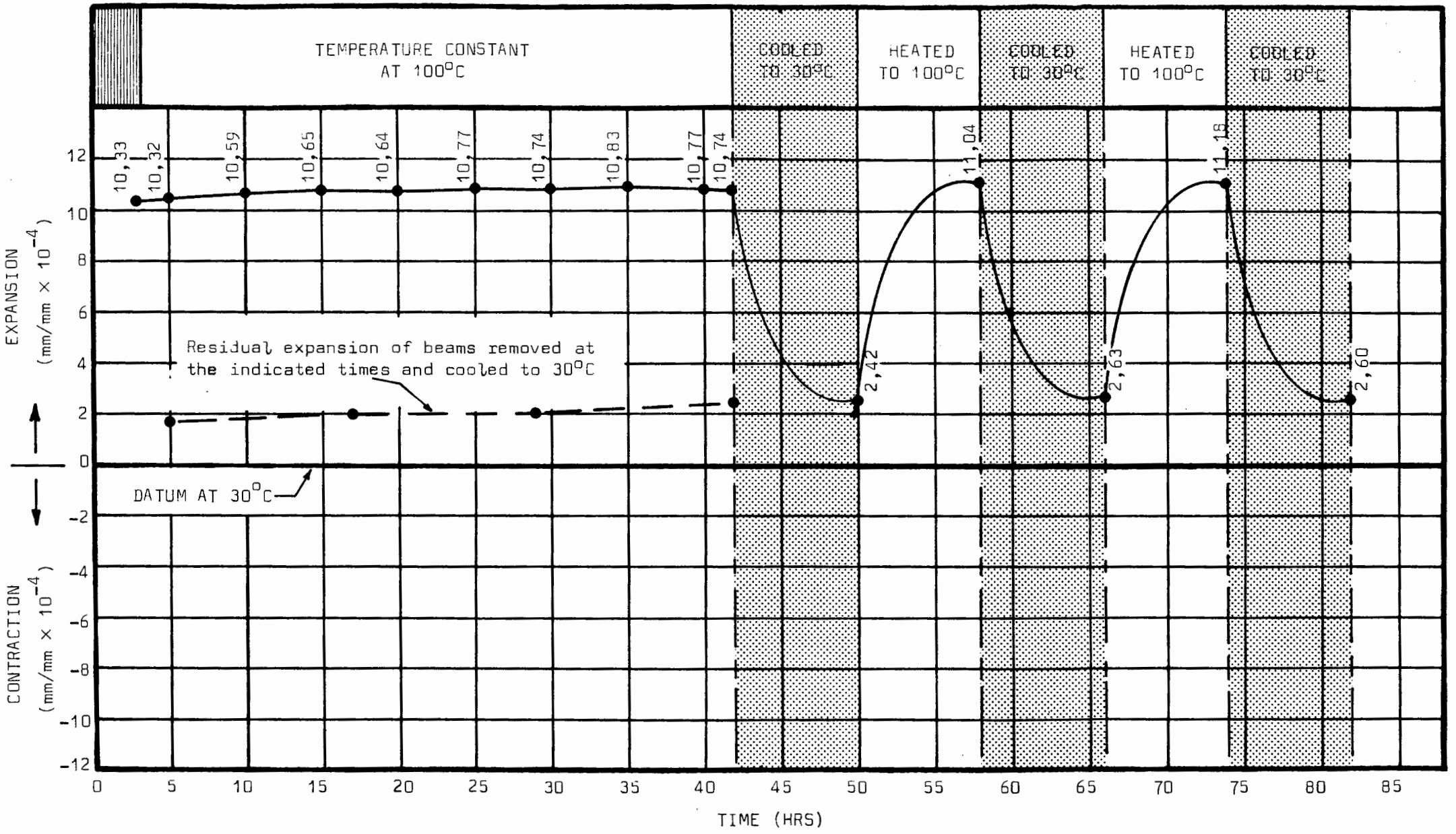


FIG.A.IV.30: The linear deformation of specimen: Mix CMX at 100°C (saturated).

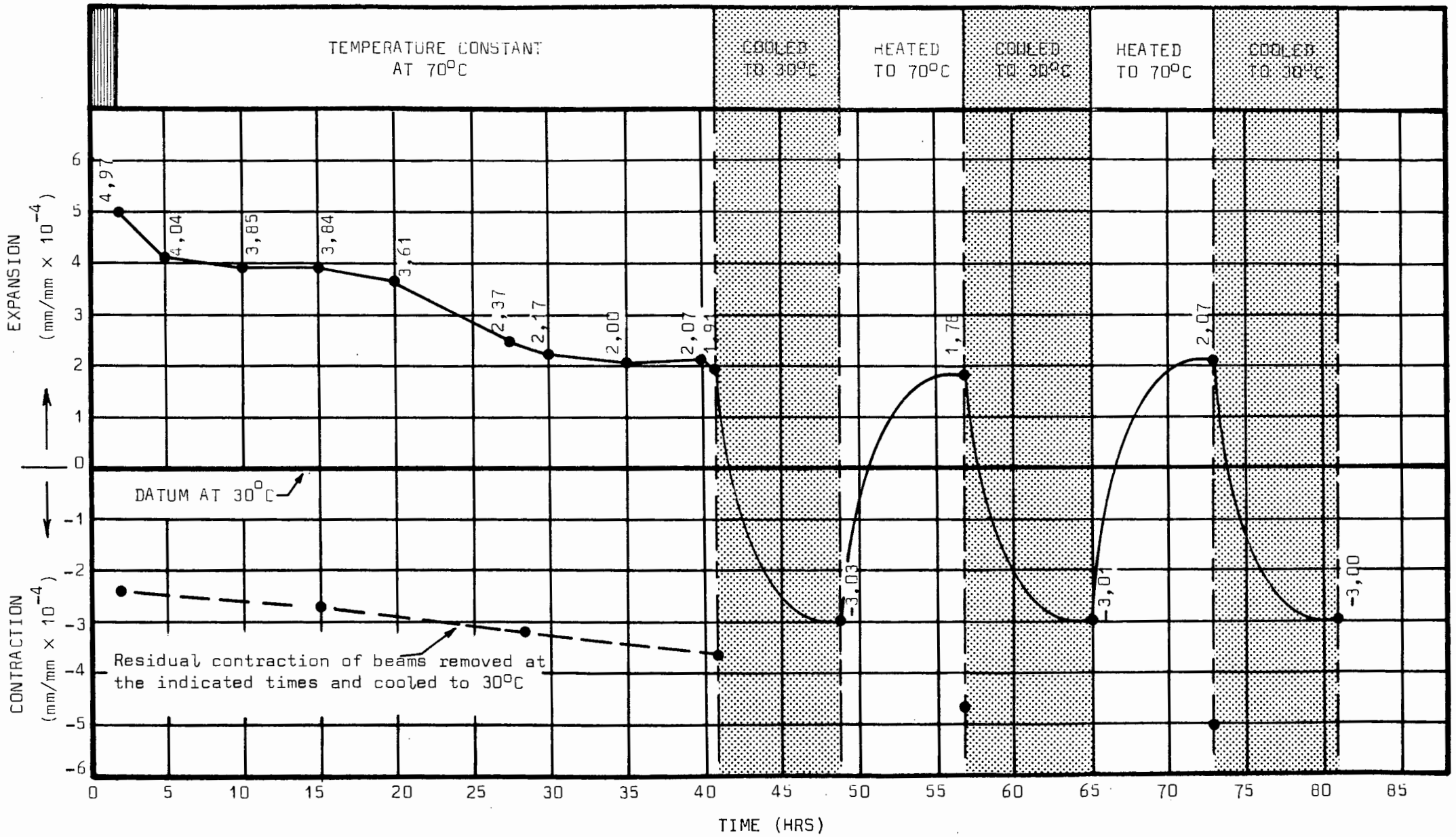


FIG.A.IV.31: The linear deformation of test specimen: Mix CMX at 70°C (dry).

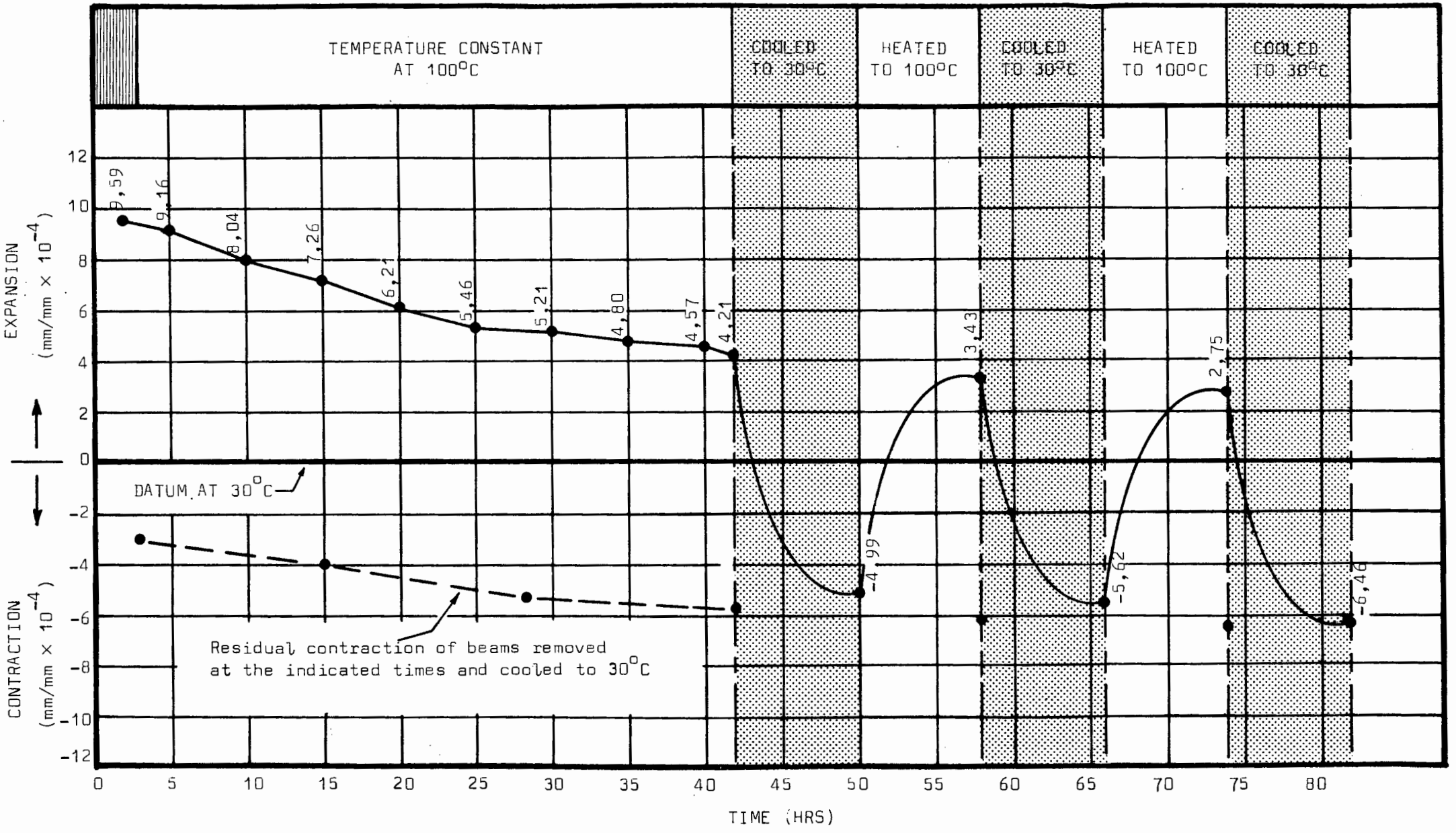


FIG.A.IV.32: The linear deformation of test specimen: Mix CMX at 100°C (dry).

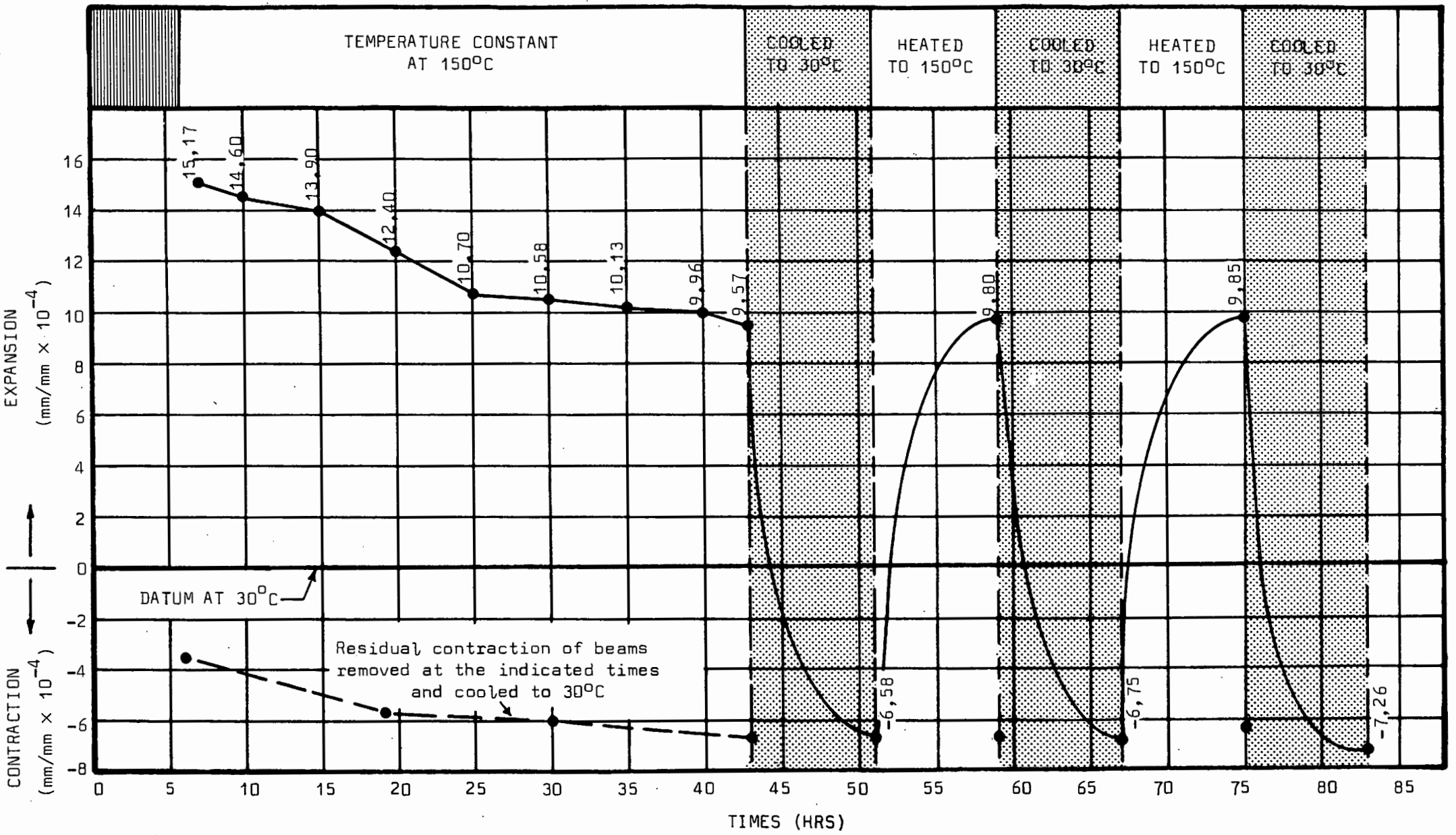


FIG.A.IV.33: The linear deformation of test specimen: Mix CMX at 150°C (dry).

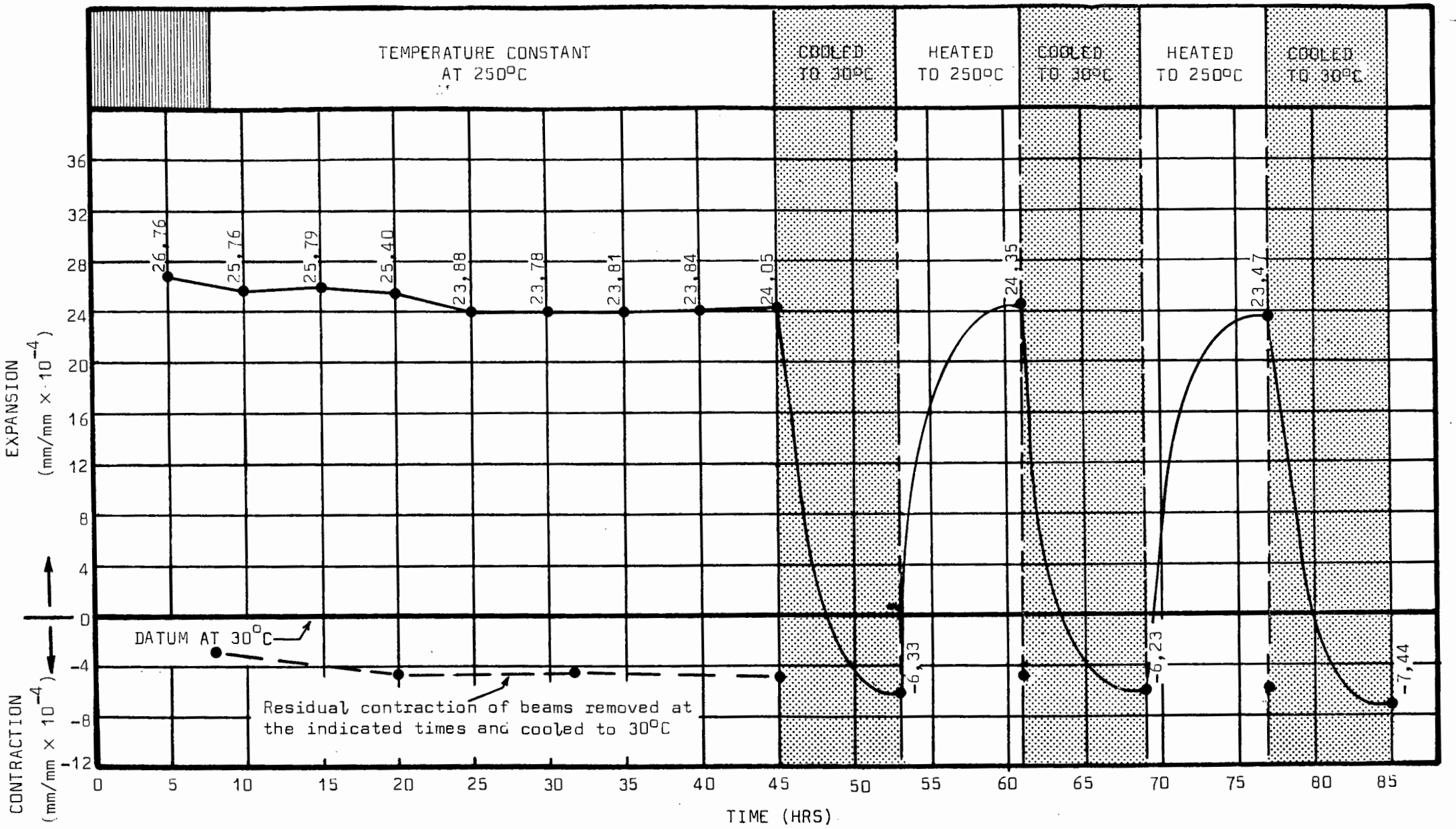


FIG.A.IV.34: The linear deformation of test specimen: Mix CMX at 250°C (dry).

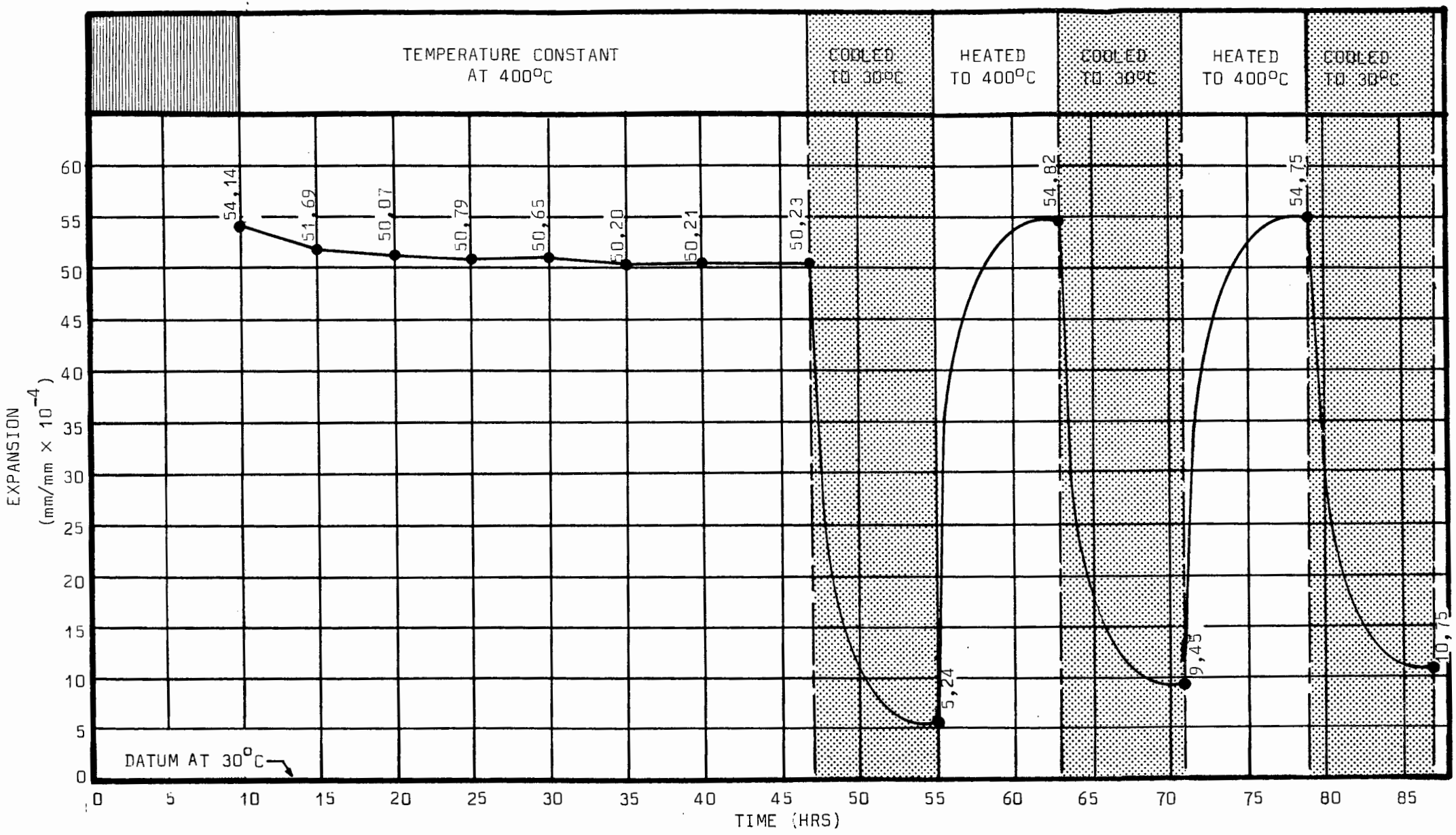


FIG.A.IV.35: The linear deformation of test specimen: Mix CMX at 400°C (dry).

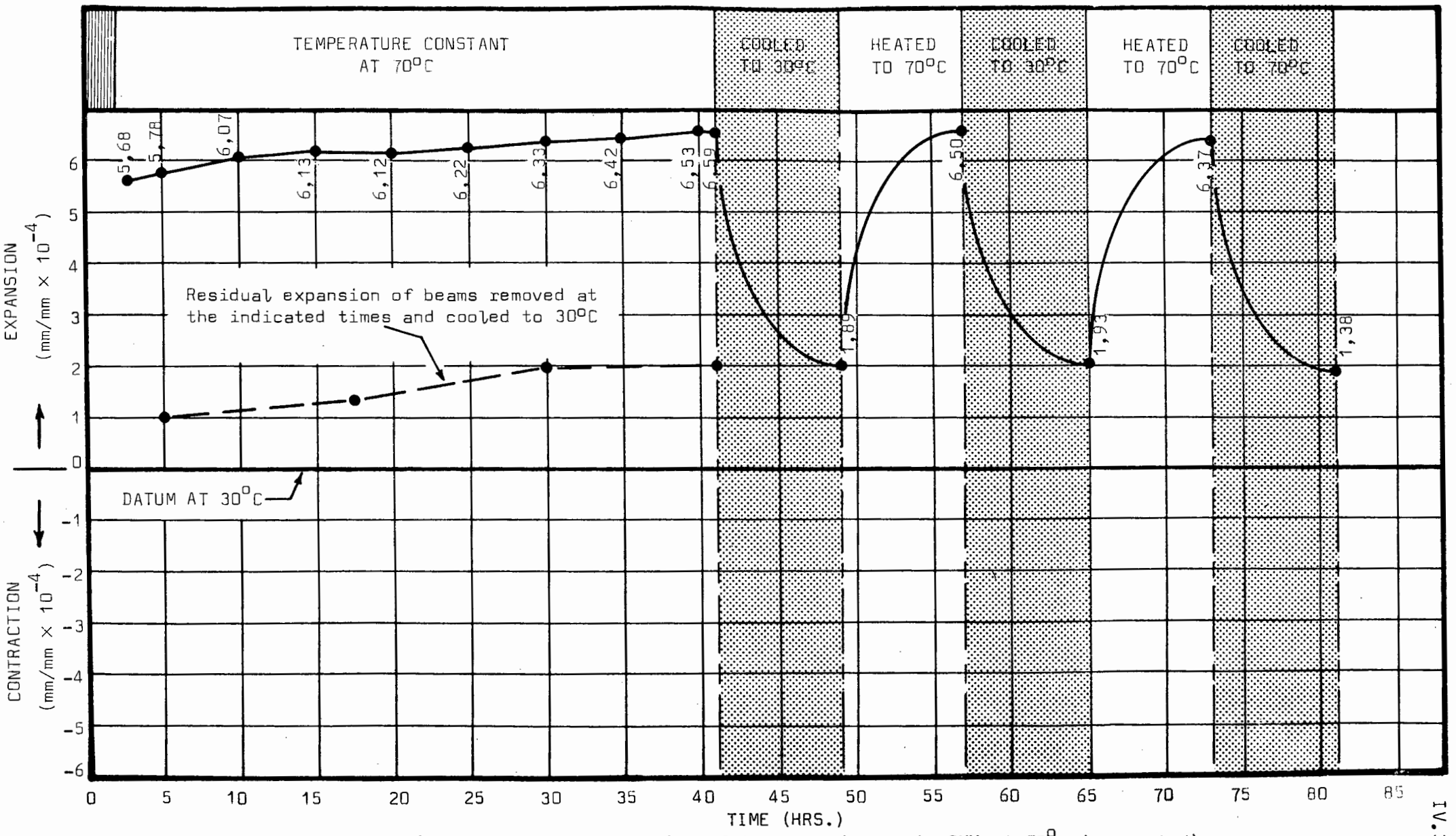


FIG.A.IV.36: The linear deformation of test specimen: Mix CMY at 70°C (saturated).

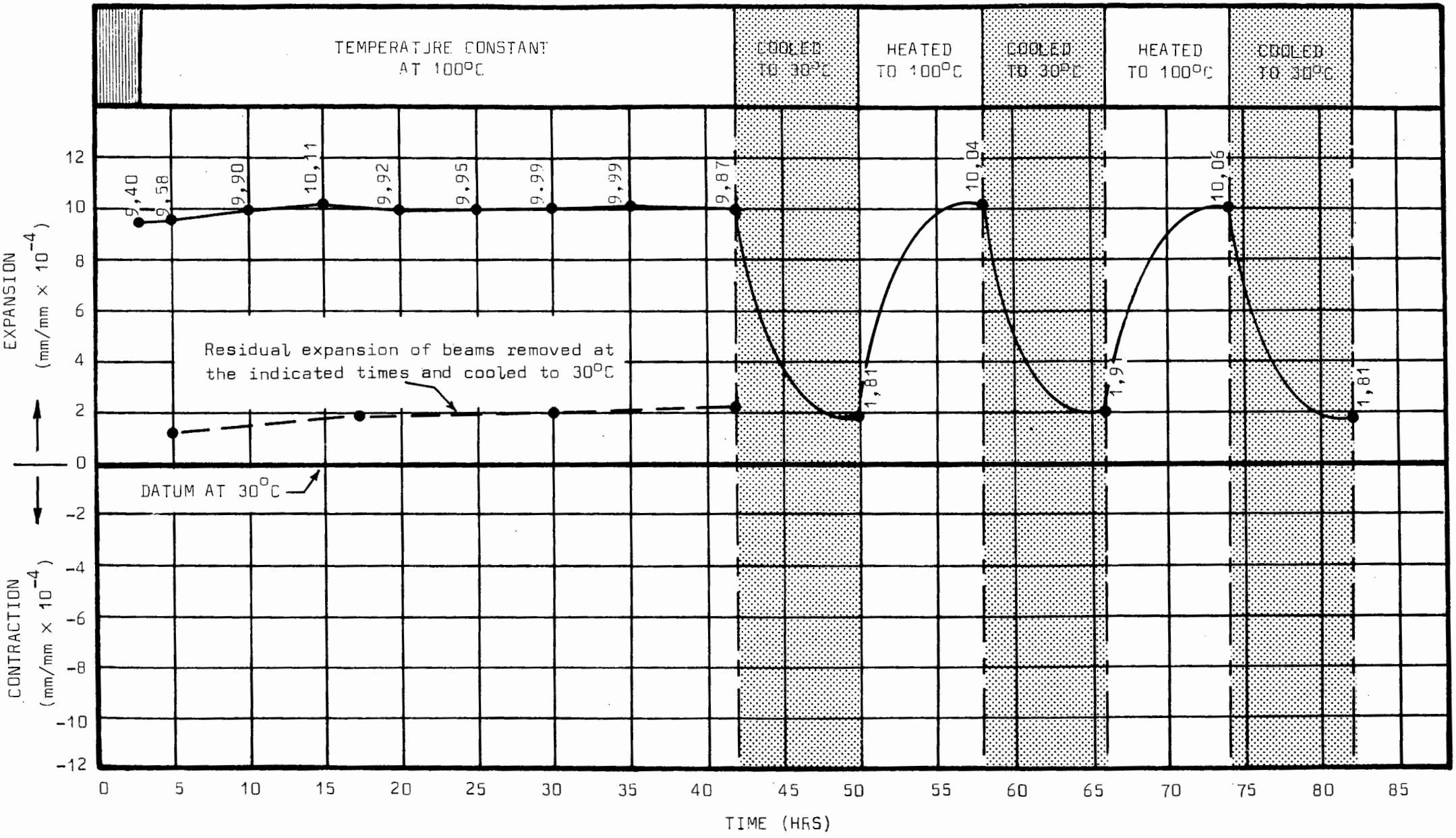


FIG.A.IV.37: The linear deformation of test specimen: Mix CMY at 100 C (saturated).

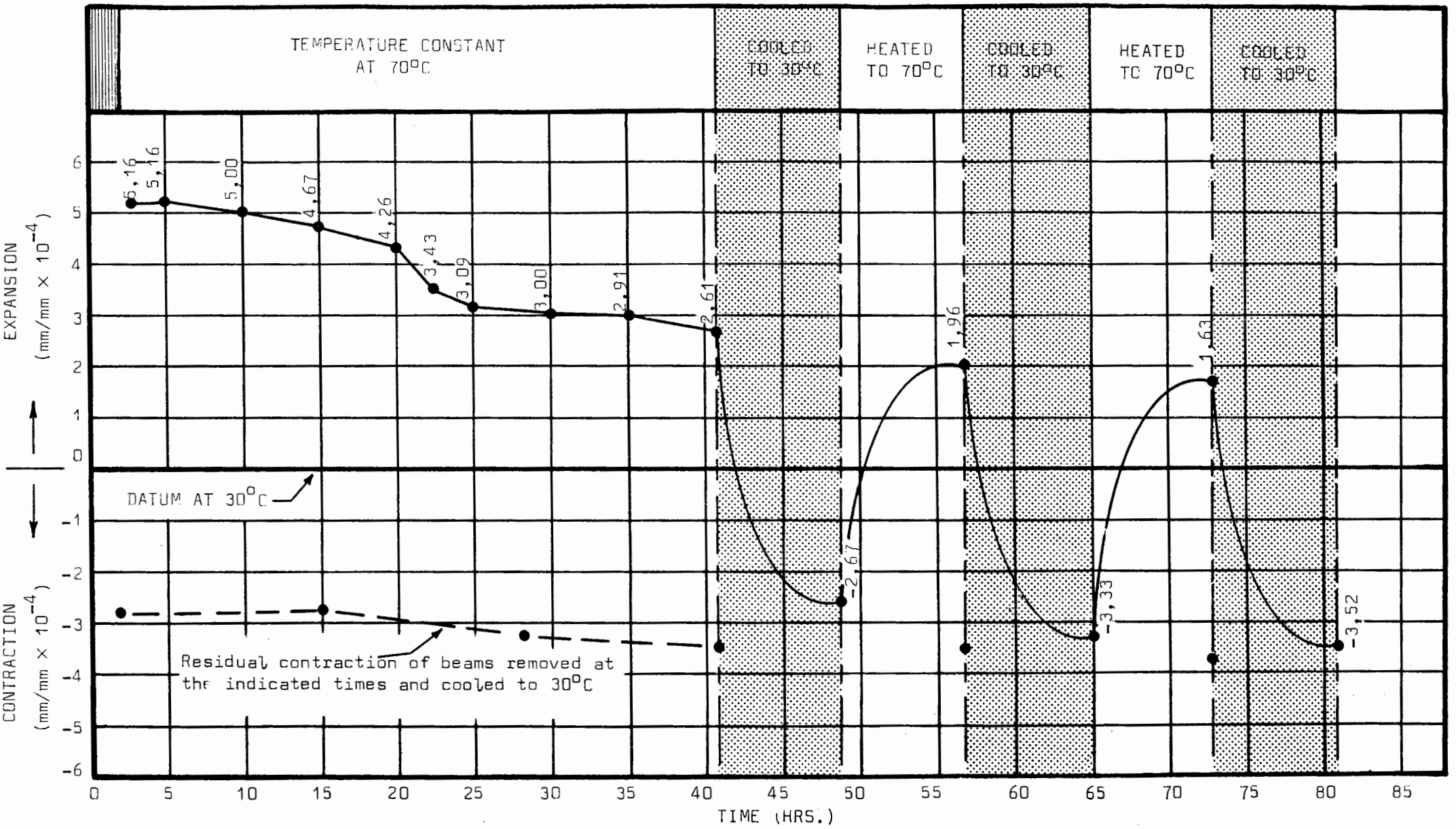


FIG.A.IV.38: The linear deformation of test specimen: Mix CMY at 70°C (dry).

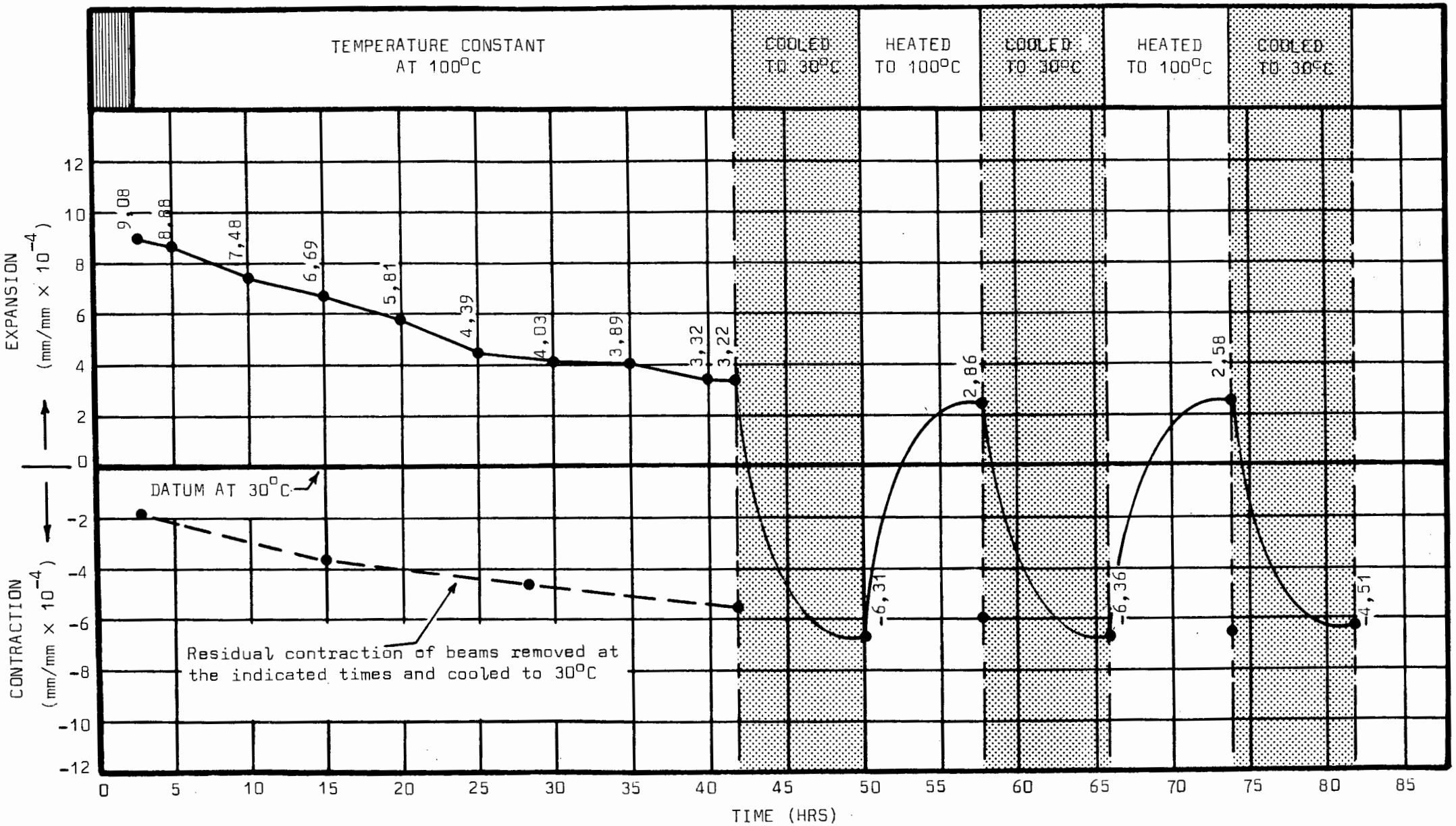


FIG.A.IV.39: The linear deformation of test specimen: Mix CMY at 100°C (dry).

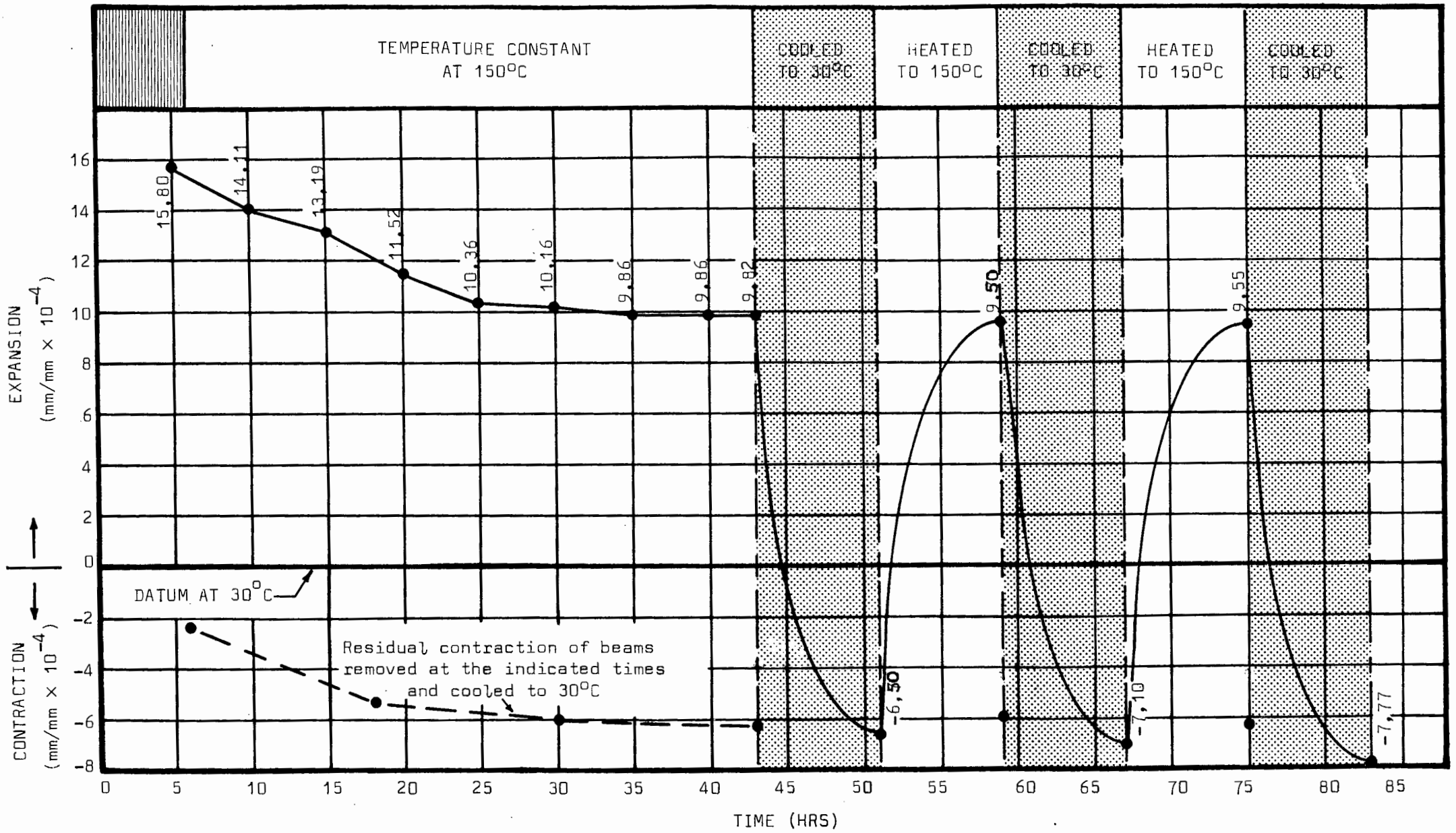


FIG.A.IV.40: The linear deformation of test specimen: Mix CMY at 150°C (dry).

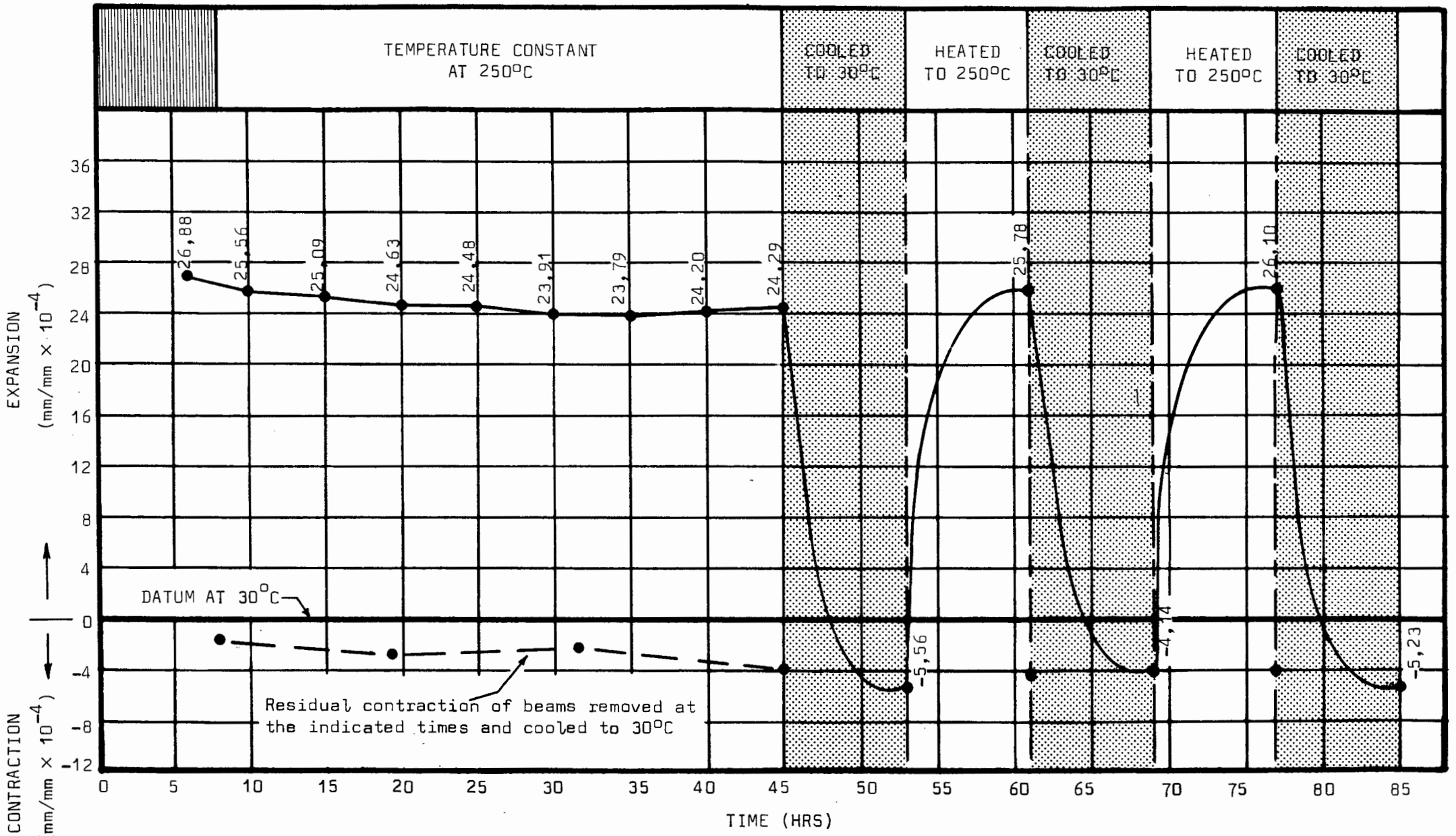


FIG.A.IV.41: The linear deformation of test specimen: Mix CMY at 250°C (dry).

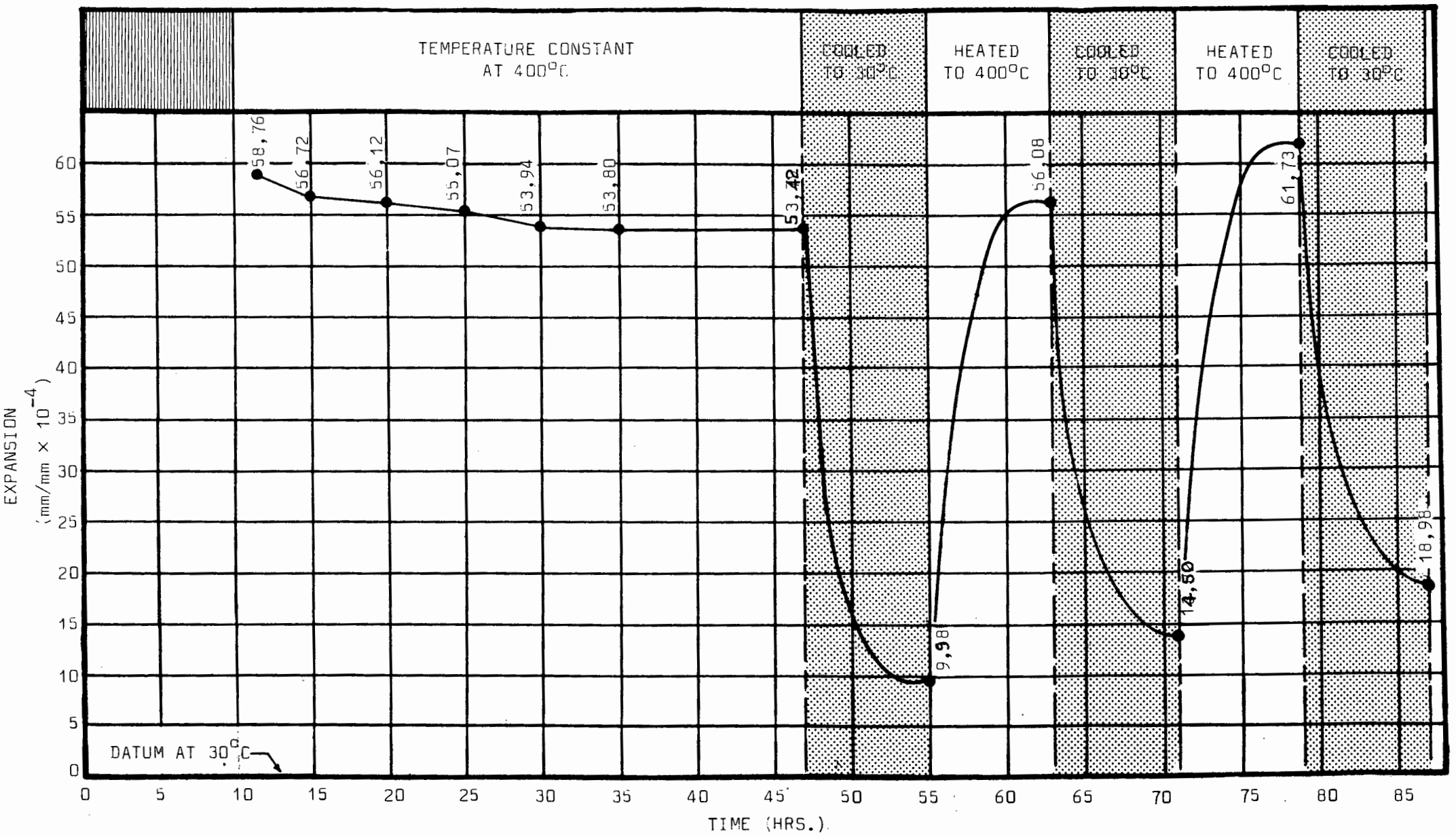


FIG.A.IV.42: The linear deformation of test specimen: Mix CMY at 400°C (dry).

APPENDIX V

V.1 The mean coded property values for concrete specimens and for mortar specimens at the various test times.

RESIDUAL LINEAR DEFORMATION* (mm/m) MEASURED AFTER COOLING

TEST TEMPS	CONCRETE MIXES						MORTAR MIXES					
	Test Times						Test Times					
	T	T + 12	T + 24	T + 36	T + 36 + 1 cycle	T + 36 + 2 cycles	T	T + 12	T + 24	T + 36	T + 36 + 1 cycle	T + 36 + 2 cycles
70° SAT	0,047	0,057	0,080	0,080	0,080	0,080	0,073	0,087	0,133	0,153	0,157	0,180
100° SAT	0,050	0,067	0,073	0,083	0,083	0,083	0,123	0,173	0,180	0,200	0,205	0,203
70° DRY	-0,150	-0,153	-0,163	-0,207	-0,207	-0,220	-0,270	-0,300	-0,330	-0,367	-0,417	-0,453
100° DRY	-0,133	-0,203	-0,237	-0,257	-0,273	-0,267	-0,240	-0,373	-0,483	-0,573	-0,623	-0,640
150° DRY	-0,187	-0,257	-0,277	-0,307	-0,283	-0,303	-0,327	-0,550	-0,627	-0,700	-0,660	-0,703
250° DRY	-0,110	-0,170	-0,170	-0,163	-0,160	-0,203	-0,200	-0,327	-0,297	-0,403	-0,463	-0,490
400° DRY	0,563	0,473	0,937	1,250	1,430	0,637	1,377	1,110	1,553	2,040	2,133	1,233

RESIDUAL LINEAR DEFORMATION* (mm/m) MEASURED AFTER RE-IMMERSION IN WATER

TEST TEMPS	CONCRETE MIXES						MORTAR MIXES					
	Test Times						Test Times					
	T	T + 12	T + 24	T + 36	T + 36 + 1 cycle	T + 36 + 2 cycles	T	T + 12	T + 24	T + 36	T + 36 + 1 cycle	T + 36 + 2 cycles
70° SAT	0,037	0,050	0,067	0,080	0,093	0,080	0,070	0,100	0,130	0,130	0,167	0,153
100° SAT	0,047	0,057	0,077	0,090	0,093	0,073	0,137	0,150	0,173	0,177	0,187	0,190
70° DRY	-0,027	-0,010	-0,033	-0,040	0,000	0,000	-0,017	-0,033	-0,040	0,043	- 0,067	0,010
100° DRY	0,003	-0,063	-0,060	-0,100	-0,097	-0,080	-0,010	-0,137	-0,200	-0,213	-0,220	-0,230
150° DRY	-0,033	-0,033	-0,047	-0,047	-0,023	-0,023	0,000	-0,003	-0,040	-0,033	-0,017	-0,017
250° DRY	0,317	0,400	0,287	0,287	0,367	0,257	0,600	0,671	0,671	0,579	0,570	0,584
400° DRY	1,287	2,463	1,397	1,607	2,233	1,097	2,683	3,327	2,857	2,703	3,317	2,637

* The mean value of the three concrete (mortar) mixes.

TABLE A.V.1.1

WATER LOSS* (%) MEASURED AFTER COOLING

TEST TEMPS	CONCRETE MIXES						MORTAR MIXES					
	Test Times						Test Times					
	T	T + 12	T + 24	T + 36	T + 36 + 1 cycle	T + 36 + 2 cycles	T	T + 12	T + 24	T + 36	T + 36 + 1 cycle	T + 36 + 2 cycles
70° SAT	0,49	0,40	-0,04	0,73	0,86	0,67	-0,07	0,37	0,43	0,60	0,70	0,63
100° SAT	0,87	1,27	1,37	0,97	0,53	0,67	0,43	0,90	0,80	0,77	0,70	0,53
70° DRY	24,57	32,37	35,20	38,03	41,30	40,77	16,53	24,27	29,57	32,37	35,70	35,47
100° DRY	37,27	52,57	57,83	61,00	63,07	61,57	30,40	45,47	55,47	58,43	62,50	61,10
150° DRY	62,27	66,13	68,27	71,17	71,43	69,87	54,13	67,07	69,23	68,73	70,33	70,20
250° DRY	72,20	74,47	74,43	76,27	78,83	69,30	71,40	71,53	73,03	72,47	73,30	73,40
400° DRY	81,83	81,03	86,73	79,57	81,37	81,77	79,57	80,70	81,70	82,70	82,97	80,40

WATER LOSS* (%) MEASURED AFTER RE-IMMERSION

TEST TEMPS	CONCRETE MIXES						MORTAR MIXES					
	Test Times						Test Times					
	T	T + 12	T + 24	T + 36	T + 36 + 1 cycle	T + 36 + 2 cycles	T	T + 12	T + 24	T + 36	T + 36 + 1 cycle	T + 36 + 2 cycles
70° SAT	-0,80	0,30	0,10	-0,04	-0,33	-0,03	-0,67	-0,13	0,07	0,10	0,17	0,00
100° SAT	0,33	0,53	0,03	0,03	-0,40	-0,10	0,23	0,33	0,17	0,53	0,10	0,20
70° DRY	4,23	2,70	3,47	3,47	3,17	2,93	4,83	4,40	4,07	4,57	4,97	4,53
100° DRY	3,67	4,30	4,53	4,60	4,77	4,67	3,70	4,70	5,13	4,77	5,03	5,13
150° DRY	4,53	5,60	5,83	5,77	4,80	5,73	5,17	7,10	5,13	5,37	6,60	6,10
250° DRY	4,20	4,10	4,27	4,00	3,57	4,17	5,57	4,53	5,47	5,50	5,20	5,07
400° DRY	2,53	0,53	2,57	1,53	0,20	2,47	3,77	2,20	3,43	2,67	1,53	3,40

* The mean value of the three concrete (mortar) mixes

TABLE A.V.1.2

COMPRESSIVE STRENGTH* (MPa) TESTED WHILST HOT

TEST TEMPS	CONCRETE MIXES						MORTAR MIXES					
	Test Times						Test Times					
	T	T + 12	T + 24	T + 36	T + 36 + 1 cycle	T + 36 + 2 cycles	T	T + 12	T + 24	T + 36	T + 36 + 1 cycle	T + 36 + 2 cycles
70° SAT	-5,56	-5,24	-5,79	-5,31	-5,36	-4,63	-4,98	-6,90	-5,05	-3,64	-4,26	-2,92
100° SAT	-9,23	-10,58	-8,00	-6,39	- 6,53	-5,41	-12,20	-12,06	-9,01	-7,92	-7,24	-5,22
70° DRY	-3,29	-1,57	-1,39	-1,18	1,93	1,71	-4,22	-3,80	-1,64	-1,12	-1,41	1,92
100° DRY	-8,51	-5,84	-4,58	-0,94	-2,54	-0,54	-7,95	-4,74	-4,28	-1,18	-0,61	- 0,78
150° DRY	-0,38	2,80	4,09	2,39	5,47	4,37	-5,54	-1,78	-0,31	-0,61	0,14	0,40
250° DRY	1,05	2,08	1,45	2,02	3,80	2,61	-0,66	2,50	1,23	0,12	0,40	0,89
400° DRY	-4,27	-1,68	-2,23	-3,00	-4,12	-2,08	-4,57	-2,96	-4,48	-6,58	-5,06	-5,34

COMPRESSIVE STRENGTH* (MPa) TESTED AFTER COOLING

TEST TEMPS	CONCRETE MIXES						MORTAR MIXES					
	Test Times						Test Times					
	T	T + 12	T + 24	T + 36	T + 36 + 1 cycle	T + 36 + 2 cycles	T	T + 12	T + 24	T + 36	T + 36 + 1 cycle	T + 36 + 2 cycles
70° SAT	-1,30	-4,27	-4,01	-3,23	-3,46	-3,64	0,21	-2,46	-2,36	-2,74	-1,88	-3,16
100° SAT	-7,77	-8,48	-7,22	-5,04	-4,29	-4,01	-8,90	-8,38	-6,69	-4,77	-3,99	-4,48
70° DRY	1,82	1,10	2,33	0,77	1,66	1,56	2,76	1,03	4,22	4,50	4,50	3,15
100° DRY	-4,35	-3,20	-3,86	-0,33	-1,87	-0,09	-2,27	-3,34	0,09	0,20	1,21	1,86
150° DRY	-1,16	4,58	3,57	4,43	3,86	4,75	-2,99	-1,64	-2,87	-1,32	3,47	3,59
250° DRY	-2,97	-1,97	-1,77	-1,94	-1,14	-1,91	-4,33	-3,56	-6,46	-3,82	-3,25	-4,10
400° DRY	-7,74	-8,43	-10,52	-10,73	-7,91	-6,48	-12,98	-12,89	-15,22	-15,42	-14,96	-13,27

* The mean coded value of the three concrete (mortar) mixes.

TABLE A.V.1.3

COMPRESSIVE STRENGTH* (MPa) TESTED WET AFTER RE-IMMERSION

TEST TEMPS	CONCRETE MIXES						MORTAR MIXES					
	Test Times						Test Times					
	T	T + 12	T + 24	T + 36	T + 36 + 1 cycle	T + 36 + 2 cycles	T	T + 12	T + 24	T + 36	T + 36 + 1 cycle	T + 36 + 2 cycles
70° SAT	0,64	-0,79	-2,97	-2,34	-2,80	-2,33	2,29	-2,07	-1,27	-0,84	-2,84	1,03
100° SAT	-3,92	-6,33	-5,76	-4,21	-4,98	-2,31	- 7,37	-6,49	-6,00	-6,20	-6,23	-5,28
70° DRY	-0,84	-2,65	-3,45	-1,99	-2,90	-1,94	0,66	-2,44	-2,56	-1,72	-4,25	-1,92
100° DRY	-6,27	-9,09	-9,98	-8,66	-10,61	-12,63	-4,57	-5,66	-7,15	-8,27	-5,11	-8,01
150° DRY	-8,57	-10,29	-9,15	-10,49	-9,17	-10,48	-8,87	-12,32	-12,95	-13,52	-11,51	-11,71
250° DRY	-10,93	-11,36	-10,07	-10,21	-9,03	-10,20	-10,48	-14,10	-12,84	-12,26	-13,35	-11,92
400° DRY	-10,61	-10,84	-10,55	-9,35	-11,41	-7,22	-14,33	-13,07	-14,15	-12,29	-14,32	-14,61

* The mean coded value of the three concrete (mortar) mixes.

TABLE A.V.1.4

PULSE VELOCITY* (m/sec) TESTED AFTER COOLING

TEST TEMPS	CONCRETE MIXES						MORTAR MIXES					
	Test Times						Test Times					
	T	T + 12	T + 24	T + 36	T + 36 + 1 cycle	T + 36 + 2 cycles	T	T + 12	T + 24	T + 36	T + 36 + 1 cycle	T + 36 + 2 cycles
70° SAT	-41,3	-104,7	-88,3	-115,0	-116,0	-40,7	-22,0	-69,3	-110,7	-63,3	-83,3	-128,0
100° SAT	-116,0	-161,0	-152,7	-134,0	-141,7	-125,0	-277,0	-358,0	-286,7	-387,3	-346,0	-357,7
70° DRY	-150,7	-197,0	-167,0	-260,0	-250,7	-248,3	-131,7	-298,0	-269,3	-320,3	-317,7	-337,7
100° DRY	-290,3	-375,0	-413,7	-405,7	-429,3	-406,0	-415,3	-497,7	-542,7	-547,3	-572,7	-537,0
150° DRY	-386,3	-469,7	-538,3	-595,7	-559,3	-637,7	-685,7	-752,0	-820,0	-772,3	-812,7	-822,7
250° DRY	-885,0	-876,0	-867,3	-963,7	-1064,7	-797,3	-1152,0	-1098,0	-1194,0	-1224,0	-1324,0	-1202,1
400° DRY	-1603,0	-1576,0	-1836,0	-2274,0	-2011,3	-1925,0	-1974,0	-1908,0	-2016,0	-2155,8	-2082,0	-2101,0

PULSE VELOCITY* (m/sec) TESTED AFTER RE-IMMERSION

TEST TEMPS	CONCRETE MIXES						MORTAR MIXES					
	Test Times						Test Times					
	T	T + 12	T + 24	T + 36	T + 36 + 1 cycle	T + 36 + 2 cycles	T	T + 12	T + 24	T + 36	T + 36 + 1 cycle	T + 36 + 2 cycles
70° SAT	-13,3	-50,0	-31,7	-41,7	-42,0	-13,0	-8,0	-43,0	-43,0	-84,3	-56,3	-71,7
100° SAT	-79,7	-98,0	-51,3	-143,7	-125,0	-60,7	-188,0	-276,7	-312,0	-264,3	-277,7	-271,0
70° DRY	-96,0	-58,7	-94,3	-120,7	-104,7	-22,0	-63,3	-97,3	-97,3	-123,3	-166,7	-131,0
100° DRY	-107,0	-185,3	-215,3	-160,7	-231,3	-248,3	-264,3	-397,0	-448,7	-475,0	-476,7	-498,3
150° DRY	-282,3	-358,3	-300,0	-348,7	-283,0	-317,0	-498,7	-527,3	-584,0	-568,3	-604,7	-600,3
250° DRY	-291,7	-274,0	-179,3	-197,0	-179,0	-215,0	-543,3	-526,7	-527,0	-505,0	-500,0	-516,0
400° DRY	-308,3	-274,0	-317,3	-255,7	-321,7	-197,0	-397,0	-332,7	-407,3	-393,3	-314,3	-399,0

* The mean coded value of the three concrete (mortar) mixes.

TABLE A.V.1.5

DYNAMIC YOUNG'S MODULUS* (GPa) TESTED AFTER COOLING

TEST TEMPS	CONCRETE MIXES						MORTAR MIXES					
	Test Times						Test Times					
	T	T + 12	T + 24	T + 36	T + 36 + 1 cycle	T + 36 + 2 cycles	T	T + 12	T + 24	T + 36	T + 36 + 1 cycle	T + 36 + 2 cycles
70° SAT	-2,49	-3,26	-3,68	-3,68	-4,27	-4,14	-1,53	-1,52	-1,88	-2,31	-2,41	-2,44
100° SAT	-4,45	-4,77	-6,02	-5,47	-5,07	-4,61	-4,47	-5,42	-5,60	-5,82	-5,04	-5,60
70° DRY	-2,02	-2,84	-2,88	-3,50	-4,35	-4,23	-1,41	-2,38	-2,53	-3,26	-2,96	-3,06
100° DRY	-6,50	-7,10	-7,02	-7,02	-7,74	-7,87	-3,84	-4,83	-5,63	-5,71	-6,00	-5,89
150° DRY	-8,09	-8,27	-9,14	-9,54	-10,61	-9,81	-8,23	-9,29	-9,89	-9,44	-9,16	-9,26
250° DRY	-16,61	-17,44	-17,37	-18,75	-19,69	-18,02	-14,26	-13,62	-15,00	-14,76	-15,62	-14,63
400° DRY	-28,14	-27,93	-29,61	-32,71	-32,23	-29,26	-21,18	-21,08	-21,86	-23,34	-23,17	-22,37

DYNAMIC YOUNG'S MODULUS* (GPa) TESTED AFTER RE-IMMERSION

TEST TEMPS	CONCRETE MIXES						MORTAR MIXES					
	Test Times						Test Times					
	T	T + 12	T + 24	T + 36	T + 36 + 1 cycle	T + 36 + 2 cycles	T	T + 12	T + 24	T + 36	T + 36 + 1 cycle	T + 36 + 2 cycles
70° SAT	-1,08	-2,06	-2,13	-2,44	-2,68	-2,42	-0,32	-1,30	-1,14	-2,32	-1,51	-1,60
100° SAT	-3,68	-4,20	-4,52	-4,93	-4,41	-3,31	-3,24	-4,32	-5,32	-4,72	-4,91	-4,28
70° DRY	0,14	-1,84	-1,53	-2,25	-1,76	-0,63	-1,31	-1,81	-2,57	-2,40	-2,79	-3,10
100° DRY	-0,14	-3,81	-3,63	-3,43	-4,75	-3,88	-1,44	-4,07	-4,49	-4,84	-5,00	-5,33
150° DRY	-4,18	-5,72	-5,05	-5,73	-4,31	-5,13	-6,30	-6,87	-7,17	-7,46	-7,41	-7,07
250° DRY	-6,15	-5,80	-4,70	-4,60	-4,18	-5,48	-8,15	-8,32	-7,92	-7,33	-7,65	-7,65
400° DRY	-8,48	-8,45	-9,06	-6,71	-10,00	-8,06	-7,20	-5,85	-7,07	-5,81	-6,45	-5,99

* The mean coded value of the three concrete (mortar) mixes.

TABLE A.V.1.6

POISSON'S RATIO* TESTED AFTER COOLING

TEST TEMPS	CONCRETE MIXES						MORTAR MIXES					
	Test Times						Test Times					
	T	T + 12	T + 24	T + 36	T + 36 + 1 cycle	T + 36 + 2 cycles	T	T + 12	T + 24	T + 36	T + 36 + 1 cycle	T + 36 + 2 cycles
70° SAT	0,016	0,012	0,018	0,017	0,020	0,024	0,025	0,017	0,010	0,026	0,022	0,021
100° SAT	0,022	0,025	0,028	0,026	0,013	0,023	0,017	0,010	0,011	0,013	0,010	0,012
70° DRY	-0,013	-0,011	-0,032	-0,017	-0,009	-0,009	-0,019	-0,049	-0,039	-0,056	-0,049	-0,059
100° DRY	0,009	-0,006	-0,011	-0,012	-0,008	-0,004	-0,060	-0,075	-0,086	-0,089	-0,093	-0,076
150° DRY	0,001	-0,007	-0,010	-0,003	0,003	-0,002	-0,064	-0,074	-0,090	-0,073	-0,121	-0,100
250° DRY	0,019	0,028	0,029	0,034	0,031	0,048	-0,109	-0,068	-0,057	-0,050	-0,061	0,013
400° DRY	0,082	0,081	0,082	0,112	0,085	0,067	-0,058	-0,017	-0,025	0,046	0,036	-0,026

POISSON'S RATIO* TESTED AFTER RE-IMMERSION

TEST TEMPS	CONCRETE MIXES						MORTAR MIXES					
	Test Times						Test Times					
	T	T + 12	T + 24	T + 36	T + 36 + 1 cycle	T + 36 + 2 cycles	T	T + 12	T + 24	T + 36	T + 36 + 1 cycle	T + 36 + 2 cycles
7 ° SAT	0,010	0,012	0,017	0,016	0,018	0,016	0,012	0,012	0,012	0,015	-0,013	0,011
100° SAT	0,021	0,023	0,029	0,021	0,021	0,022	0,010	0,011	0,020	-0,009	0,021	-0,013
70° DRY	-0,014	0,008	0,002	0,002	-0,002	0,004	0,002	0,004	0,010	0,007	0,004	0,010
100° DRY	-0,013	0,005	-0,001	0,007	0,005	-0,001	-0,043	-0,026	-0,031	-0,031	-0,029	-0,028
150° DRY	-0,006	-0,003	0,001	-0,001	0,000	-0,002	-0,013	-0,040	-0,015	-0,005	-0,017	-0,006
250° DRY	0,013	0,010	0,011	0,012	0,013	0,016	0,016	0,021	0,018	0,009	0,018	0,014
400° DRY	0,030	0,034	0,026	0,018	0,039	0,037	0,027	0,015	0,024	0,025	0,028	0,052

* The mean coded value of the three concrete (mortar) mixes.

TABLE A.V.1.7

APPENDIX V (contd.)

V.2 The mean coded property values for the various concrete and mortar mixes. (Calculated from the coded values at test times T hrs, T + 12 hrs, T + 24 hrs and T + 36 hrs).

RESIDUAL LINEAR DEFORMATION* (mm/m) AFTER COOLING

TEST TEMPERATURE	CONCRETE MIXES			MORTAR MIXES		
	BCY	CCX	CCY	BMY	CMX	CMY
	C_1	C_2	C_3	M_4	M_5	M_6
70° SAT	0,045	0,065	0,087	0,075	0,05	0,155
100° SAT	0,045	0,070	0,090	0,133	0,197	0,177
70° DRY	-0,180	-0,172	-0,152	-0,342	-0,302	-0,305
100° DRY	-0,210	-0,217	-0,195	-0,405	-0,452	-0,395
150° DRY	-0,225	-0,267	-0,277	-0,597	-0,560	-0,495
250° DRY	-0,133	-0,197	-0,130	-0,275	-0,392	-0,252
400° DRY	0,832	1,152	0,432	1,592	1,400	1,567

RESIDUAL LINEAR DEFORMATION* (mm/m) AFTER RE-IMMERSION

TEST TEMPERATURE	CONCRETE MIXES			MORTAR MIXES		
	BCY	CCX	CCY	BMY	CMX	CMY
	C_1	C_2	C_3	M_4	M_5	M_6
70° SAT	0,042	0,060	0,072	0,075	0,100	0,147
100° SAT	0,042	0,067	0,092	0,117	0,195	0,165
70° DRY	-0,020	-0,060	-0,003	-0,110	-0,050	0,060
100° DRY	-0,058	-0,063	-0,045	-0,142	-0,145	-0,132
150° DRY	-0,008	-0,050	-0,063	-0,070	-0,075	-0,062
250° DRY	0,325	0,360	0,282	0,650	0,607	+0,625
400° DRY	1,652	2,095	1,317	2,740	2,770	3,167

* Mean value calculated from the values at test times T , T + 12 hrs, T + 24 hrs and T + 36 hrs.

TABLE A.V.2.1

WATER LOSS* (%) MEASURED AFTER COOLING

TEST TEMPERATURE	CONCRETE MIXES			MORTAR MIXES		
	BCY	CCX	CCY	BMY	CMX	CMY
	C_1	C_2	C_3	M_4	M_5	M_6
70° SAT	0,00	1,18	0,00	0,15	0,60	0,25
100° SAT	1,45	0,90	1,00	0,50	0,83	0,85
70° DRY	27,63	37,45	32,55	22,98	27,20	26,88
100° DRY	50,35	51,25	54,90	46,15	47,18	49,00
150° DRY	65,88	65,58	69,43	63,40	66,35	64,63
250° DRY	71,80	72,15	79,08	73,10	70,78	72,45
400° DRY	85,28	83,60	83,48	82,53	79,48	81,50

WATER LOSS* (%) MEASURED AFTER RE-IMMERSION

TEST TEMPERATURE	CONCRETE MIXES			MORTAR MIXES		
	BCY	CCX	CCY	BMY	CMX	CMY
	C_1	C_2	C_3	M_4	M_5	M_6
70° SAT	-0,25	0,67	-0,75	0,15	-0,05	-0,58
100° SAT	0,00	0,45	1,15	0,55	0,05	0,43
70° DRY	3,60	3,73	3,08	4,80	3,75	4,85
100° DRY	4,43	3,40	5,00	4,95	4,70	4,08
150° DRY	5,28	5,15	5,88	6,15	6,98	3,95
250° DRY	3,78	3,18	5,48	5,98	3,75	6,08
400° DRY	2,23	1,65	1,50	2,55	4,45	2,05

*Mean value calculated from the values T , T + 12 hrs, T + 24 hrs and T + 36 hrs.

TABLE A.V.2.2

COMPRESSIVE STRENGTH* (MPa) TESTED WHILST HOT

TEST TEMPERATURE	CONCRETE MIXES			MORTAR MIXES		
	BCY	CCX	CCY	BMY	CMX	CMY
	C_1	C_2	C_3	M_4	M_5	M_6
70° SAT	-5,37	-5,68	-5,38	-7,31	-4,30	-3,81
100° SAT	-9,34	-7,36	-8,95	-9,36	-11,03	-10,51
70° DRY	-2,56	-2,60	-0,42	-3,46	-1,00	3,62
100° DRY	-4,84	-3,53	-6,54	-5,40	-3,75	-4,46
150° DRY	0,97	2,98	2,73	-2,82	-1,54	-1,83
250° DRY	-0,86	3,04	2,77	-0,53	-0,24	3,17
400° DRY	-3,70	-3,66	-1,03	-4,54	-4,32	-5,08

COMPRESSIVE STRENGTH* (MPa) TESTED AFTER COOLING

TEST TEMPERATURE	CONCRETE MIXES			MORTAR MIXES		
	BCY	CCX	CCY	BMY	CMX	CMY
	C_1	C_2	C_3	M_4	M_5	M_6
70° SAT	-3,10	-3,55	-2,96	-2,41	-2,46	-0,65
100° SAT	-7,82	-5,46	-8,11	-6,52	-7,55	-7,50
70° DRY	3,40	2,74	0,63	3,11	2,92	3,32
100° DRY	-4,20	-0,75	-3,87	-2,75	-0,87	-0,30
150° DRY	2,44	2,05	2,79	-4,06	-3,61	1,05
250° DRY	-5,34	0,14	-1,29	-4,88	-5,26	-3,49
400° DRY	-11,86	-8,29	-7,92	-15,95	-12,91	-13,53

* Mean coded value calculated from the coded values at test times T , T + 12 hrs, T + 24 hrs and T + 36 hrs.

TABLE A.V.2.3

COMPRESSIVE STRENGTH* (MPa) AFTER RE-IMMERSION

TEST TEMPERATURE	CONCRETE MIXES			MORTAR MIXES		
	BCY	CCX	CCY	BMY	CMX	CMY
	C_1	C_2	C_3	M_4	M_5	M_6
70° SAT	-0,71	-1,76	-1,63	-1,50	-1,80	1,88
100° SAT	-4,63	-5,18	-5,36	-8,72	-7,41	-6,92
70° DRY	-1,88	-2,90	-1,91	-0,79	-3,11	-0,65
100° DRY	-11,00	-5,59	-8,91	-5,96	-6,38	-6,89
150° DRY	-11,78	-8,48	-8,63	-16,47	-11,55	-7,73
250° DRY	-13,74	-8,44	-9,75	-15,39	-12,17	-9,69
400° DRY	-12,47	-10,53	-8,63	-15,31	-12,24	-12,83

* Mean coded value calculated from the coded values at test times T . T + 12 hrs, T + 24 hrs and T + 36 hrs.

TABLE A.V.2.4

PULSE VELOCITY* (m/sec) MEASURED AFTER COOLING

TEST TEMPERATURE	CONCRETE MIXES			MORTAR MIXES		
	BCY	CCX	CCY	BMY	CMX	CMY
	C_1	C_2	C_3	M_4	M_5	M_6
70° SAT	-118,3	- 96,0	- 70,3	- 38,5	- 79,0	- 81,5
100° SAT	-147,0	-129,8	-146,0	-349,8	-369,0	-340,0
70° DRY	-125,0	-316,8	-139,3	-229,5	-285,8	-249,3
100° DRY	-341,0	-395,3	-377,3	-476,8	-502,5	-523,0
150° DRY	-446,0	-536,3	-510,3	-761,3	-783,8	-727,5
250° DRY	-867,8	-839,5	-986,8	-1279,0	-1214,0	-1167,0
400° DRY	-1665,8	-1835,0	-1716,0	-2164,0	-2087,0	-2198,0

PULSE VELOCITY* (m/sec) MEASURED AFTER RE-IMMERSION

TEST TEMPERATURE	CONCRETE MIXES			MORTAR MIXES		
	BCY	CCX	CCY	BMY	CMX	CMY
	C_1	C_2	C_3	M_4	M_5	M_6
70° SAT	- 60,8	70,3	-112,0	- 49,3	- 48,3	- 36,3
100° SAT	-146,3	- 48,8	- 84,5	-185,5	-332,3	-263,0
70° DRY	- 68,0	-188,0	- 21,3	- 65,8	-133,3	- 87,0
100° DRY	-201,5	-174,3	-125,5	-340,0	-428,8	-420,0
150° DRY	-328,8	-331,0	-307,3	-561,5	-635,6	-511,8
250° DRY	-236,0	-231,0	-239,0	-574,5	-527,0	-475,0
400° DRY	-282,3	-282,0	-302,3	-298,3	-344,8	-429,8

*Mean coded value calculated from the coded values at test times T , T + 12 hrs, T + 24 hrs and T + 36 hrs.

TABLE A.V.2.5

DYNAMIC YOUNG'S MODULUS* (GPa) TESTED AFTER COOLING

TEST TEMPERATURE	CONCRETE MIXES			MORTAR MIXES		
	BCY	CCX	CCY	BMY	CMX	CMY
	C_1	C_2	C_3	M_4	M_5	M_6
70° SAT	-3,49	-3,05	-3,20	-2,41	-1,89	-2,34
100° SAT	-5,33	-5,77	-5,94	-3,86	-5,93	-6,19
70° DRY	-2,63	-6,27	-0,47	-2,80	-0,96	-3,39
100° DRY	-4,78	-5,56	-10,39	-5,12	-4,86	-5,03
150° DRY	-8,87	-8,50	-8,91	-10,35	-8,94	-8,36
250° DRY	-21,33	-15,64	-15,67	-14,46	-13,70	-15,06
400° DRY	-28,74	-31,36	-28,70	-21,72	-20,92	-22,96

DYNAMIC YOUNG'S MODULUS* (GPa) TESTED AFTER RE-IMMERSION

TEST TEMPERATURE	CONCRETE MIXES			MORTAR MIXES		
	BCY	CCX	CCY	BMY	CMX	CMY
	C_1	C_2	C_3	M_4	M_5	M_6
70° SAT	-1,60	-2,22	-2,10	-1,20	-1,22	-1,40
100° SAT	-3,87	-4,52	-4,62	-3,13	-4,26	-5,82
70° DRY	-1,12	-5,87	2,89	-0,36	-0,22	-5,49
100° DRY	-1,35	-1,38	-5,53	-4,25	-3,50	-3,39
150° DRY	-6,22	-3,74	-5,55	-8,76	-6,47	-5,63
250° DRY	-3,65	-5,58	-6,70	-7,93	-8,07	-7,80
400° DRY	-6,91	-12,76	-5,01	-2,94	-6,13	-10,16

* Mean coded values calculated from the coded values at test times T , T + 12hrs, T + 24 hrs, and T + 36 hrs.

TABLE A.V.2.6

POISSON'S RATIO* : TESTED AFTER COOLING

TEST TEMPERATURE	CONCRETE MIXES			MORTAR MIXES		
	BCY	CCX	CCY	BMY	CMX	CMY
	C_1	C_2	C_3	M_4	M_5	M_6
70° SAT	0,014	0,013	0,019	0,021	0,013	0,024
100° SAT	0,021	0,026	0,028	-0,003	0,018	0,020
70° DRY	0,001	-0,001	-0,054	-0,021	-0,081	-0,021
100° DRY	-0,017	-0,024	0,027	-0,052	-0,081	-0,100
150° DRY	0,002	-0,009	-0,008	-0,035	-0,097	-0,094
250° DRY	0,069	0,020	-0,005	-0,097	-0,094	-0,022
400° DRY	0,069	0,118	0,080	-0,050	-0,023	0,035

POISSON'S RATIO* : TESTED AFTER RE-IMMERSION

TEST TEMPERATURE	CONCRETE MIXES			MORTAR MIXES		
	BCY	CCX	CCY	BMY	CMX	CMY
	C_1	C_2	C_3	M_4	M_5	M_6
70° SAT	0,008	0,028	0,005	0,007	0,012	0,019
100° SAT	0,010	0,030	0,030	0,015	0,002	0,029
70° DRY	0,002	0,022	-0,026	-0,010	-0,030	0,056
100° DRY	-0,015	-0,014	0,028	-0,005	-0,044	-0,049
150° DRY	0,007	-0,018	0,004	0,020	-0,050	-0,025
250° DRY	-0,004	0,015	0,024	0,003	0,019	0,025
400° DRY	0,020	0,063	-0,002	-0,018	0,022	0,064

*Mean coded values calculated from the coded values at test times T , T + 12 hrs, T + 24 hrs and T + 36 hrs.

TABLE A.V.2.7

APPENDIX V (contd.)

V.3 The mean coded property values for the various concrete and mortar mixes. (Calculated from the coded values at test times T + 36 hrs, T + 36 hrs + 1 cycle and T + 36 hrs + 2 cycles).

RESIDUAL LINEAR DEFORMATION* (mm/m) MEASURED AFTER COOLING

TEST TEMPERATURE	CONCRETE MIXES			MORTAR MIXES		
	BCY	CCX	CCY	BMY	CMX	CMY
	C_1	C_2	C_3	M_4	M_5	M_6
70° SAT	0,063	0,090	0,087	0,143	0,133	0,213
100° SAT	0,063	0,087	0,100	0,160	0,250	0,197
70° DRY	-0,217	-0,230	-0,187	-0,400	-0,473	-0,363
100° DRY	-0,267	-0,287	-0,243	-0,577	-0,620	-0,640
150° DRY	-0,280	-0,303	-0,310	-0,790	-0,663	-0,610
250° DRY	-0,180	-0,197	-0,150	-0,433	-0,510	-0,413
400° DRY	1,193	1,157	0,967	1,680	1,913	1,813

RESIDUAL LINEAR DEFORMATION* (mm/m) MEASURED AFTER RE-IMMERSION IN WATER

TEST TEMPERATURE	CONCRETE MIXES			MORTAR MIXES		
	BCY	CCX	CCY	BMY	CMX	CMY
	C_1	C_2	C_3	M_4	M_5	M_6
70° SAT	0,057	0,100	0,097	0,100	0,153	0,197
100° SAT	0,057	0,090	0,110	0,137	0,277	0,190
70° DRY	-0,040	0,023	-0,023	-0,160	-0,020	-0,080
100° DRY	-0,103	-0,100	-0,073	-0,217	-0,243	-0,203
150° DRY	-0,010	-0,027	-0,057	-0,093	-0,080	-0,053
250° DRY	0,343	0,280	0,287	0,660	0,560	0,597
400° DRY	1,507	2,017	1,413	2,710	2,640	3,127

*Mean value calculated from the values at test times (T + 36 hrs), (T + 36 hrs + 1 cycle) and (T + 36 hrs + 2 cycles).

TABLE A.V.3.1

WATER LOSS* (%) MEASURED AFTER COOLING

TEST TEMPERATURE	CONCRETE MIXES			MORTAR MIXES		
	BCY	CCX	CCY	BMY	CMX	CMY
	C_1	C_2	C_3	M_4	M_5	M_6
70° SAT	0,08	0,89	0,57	0,40	0,93	0,60
100° SAT	0,16	0,20	0,37	0,77	0,63	0,60
70° DRY	35,73	45,93	38,43	30,77	37,83	34,93
100° DRY	56,30	64,00	65,33	59,50	61,00	61,53
150° DRY	70,40	68,53	71,30	71,30	69,17	68,80
250° DRY	68,63	74,17	81,60	75,80	70,70	72,67
400° DRY	84,97	85,63	79,27	82,73	80,33	83,00

WATER LOSS* (%) MEASURED AFTER RE-IMMERSION IN WATER

TEST TEMPERATURE	CONCRETE MIXES			MORTAR MIXES		
	BCY	CCX	CCY	BMY	CMX	CMY
	C_1	C_2	C_3	M_4	M_5	M_6
70° SAT	-0,10	0,40	0,70	0,33	0,27	0,33
100° SAT	-0,43	0,60	0,57	0,53	-0,10	0,50
70° DRY	3,50	3,50	2,57	5,33	3,57	5,17
100° DRY	4,83	3,80	5,40	5,30	5,56	4,07
150° DRY	5,03	5,30	5,97	6,77	7,83	3,47
250° DRY	2,87	3,43	5,43	6,80	3,16	5,80
400° DRY	2,20	1,00	1,00	2,33	3,33	1,93

* Mean value calculated from the values at test times (T + 36 hrs), (T + 36 hrs + 1 cycle), and (T + 36 hrs + 2 cycles).

TABLE A.V.3.2

COMPRESSIVE STRENGTH* (MPa) MEASURED WHILST HOT

TEST TEMPERATURE	CONCRETE MIXES			MORTAR MIXES		
	BCY	CCX	CCY	BMY	CMX	CMY
	C_1	C_2	C_3	M_4	M_5	M_6
70° SAT	-5,38	-5,33	-4,59	-5,54	-4,18	-1,11
100° SAT	-7,14	-5,10	-6,09	-7,95	-6,62	-5,82
70° DRY	0,95	0,01	1,49	0,37	-0,39	-0,60
100° DRY	-1,98	-0,56	-2,48	-1,81	-0,96	0,21
150° DRY	4,77	3,23	4,24	0,31	-0,76	0,39
250° DRY	-1,91	4,90	5,45	-0,78	1,34	1,85
400° DRY	-5,13	-3,37	-0,70	-5,32	-5,38	-6,28

COMPRESSIVE STRENGTH* (MPa) MEASURED AFTER COOLING

TEST TEMPERATURE	CONCRETE MIXES			MORTAR MIXES		
	BCY	CCX	CCY	BMY	CMX	CMY
	C_1	C_2	C_3	M_4	M_5	M_6
70° SAT	-2,98	-3,75	-3,60	-2,18	-3,09	-2,51
100° SAT	-3,64	-4,90	-4,80	-3,53	-5,18	-4,52
70° DRY	3,78	-0,04	0,25	3,96	1,96	6,18
100° DRY	-1,71	1,39	-2,88	1,23	0,62	1,42
150° DRY	5,14	2,48	3,70	1,52	0,47	3,74
250° DRY	-3,38	-0,10	-1,50	-2,33	-6,82	-2,03
400° DRY	-11,22	-7,05	-6,84	-17,23	-12,96	-13,45

* Mean coded value calculated from the coded values at test times (T + 36 hrs), (T + 36 hrs + 1 cycle), and (T + 36 hrs + 2 cycles).

TABLE A.V.3.3

COMPRESSIVE STRENGTH* (MPa) MEASURED AFTER RE-IMMERSION IN WATER

TEST TEMPERATURE	CONCRETE MIXES			MORTAR MIXES		
	BCY	CCX	CCY	BMY	CMX	CMY
	C_1	C_2	C_3	M_4	M_5	M_6
70° SAT	-2,21	-2,74	-2,52	-2,07	-2,80	-0,16
100° SAT	-2,95	-4,23	-4,23	-4,05	-7,28	-6,39
70° DRY	-2,81	-2,57	-1,44	-2,44	-3,77	-1,68
100° DRY	-12,57	-9,06	-10,00	-6,66	-7,65	-7,08
150° DRY	-11,17	-7,97	-8,68	-15,59	-11,79	-9,37
250° DRY	-13,05	-7,62	-8,76	-14,73	-12,96	-9,83
400° DRY	-9,44	-9,34	-9,19	-14,90	-12,36	-13,98

* Mean coded value calculated from the coded values at test time (T + 36 hrs), (T + 36 hrs + 1 cycle), and (T + 36 hrs + 2 cycles).

TABLE A.V.3.4

DYNAMIC YOUNG'S MODULUS* (GPa) MEASURED AFTER COOLING

TEST TEMPERATURE	CONCRETE MIXES			MORTAR MIXES		
	BCY	CCX	CCY	BMY	CMX	CMY
	C_1	C_2	C_3	M_4	M_5	M_6
70° SAT	-4,21	-4,04	-3,84	-4,70	-2,46	-3,00
100° SAT	-4,63	-5,35	-5,16	-4,24	-5,98	-6,25
70° DRY	-3,90	-7,94	-0,24	-2,82	-2,25	-4,22
100° DRY	-4,79	-6,21	-7,63	-6,27	-5,59	-5,75
150° DRY	-10,63	-9,41	-10,38	-10,94	-8,37	-8,55
250° DRY	-21,48	-16,77	-18,21	-14,41	-14,59	-16,00
400° DRY	-30,72	-32,04	-31,44	-22,72	-22,57	-23,59

DYNAMIC YOUNG'S MODULUS* (GPa) MEASURED AFTER RE-IMMERSION IN WATER

TEST TEMPERATURE	CONCRETE MIXES			MORTAR MIXES		
	BCY	CCX	CCY	BMY	CMX	CMY
	C_1	C_2	C_3	M_4	M_5	M_6
70° SAT	-1,63	-2,78	-3,13	-1,69	-1,76	-1,98
100° SAT	-3,35	-4,17	-5,12	-3,49	-4,40	-6,02
70° DRY	-1,50	-6,22	3,09	-1,15	-1,20	-5,94
100° DRY	-2,19	-3,46	-6,41	-5,23	-4,76	-5,18
150° DRY	-6,03	-4,00	-5,13	-8,89	-6,47	-6,58
250° DRY	-2,85	-5,25	-6,16	-7,30	-8,06	-7,27
400° DRY	-5,81	-4,59	-4,56	-0,68	-0,39	-11,17

*Mean coded value calculated from the coded values at test times (T + 36 hrs), (T + 36 hrs + 1 cycle) and (T + 36 hrs + 2 cycles).

TABLE A.V.3.5

ULTRASONIC PULSE VELOCITY* (m/sec) MEASURED AFTER COOLING

TEST TEMPERATURE	CONCRETE MIXES			MORTAR MIXES		
	BCY	CCX	CCY	BMY	CMX	CMY
	C_1	C_2	C_3	M_4	M_5	M_6
70° SAT	-87,3	-111,7	-72,7	-72,3	-99,0	-103,3
100° SAT	-126,0	-128,7	-146,0	-396,0	-375,7	-319,3
70° DRY	-153,3	-432,7	-173,0	-264,0	-404,0	-307,7
100° DRY	-376,3	-455,7	-409,0	-530,0	-564,3	-562,7
150° DRY	-499,0	-579,7	-614,0	-829,7	-802,7	-775,3
250° DRY	-907,0	-920,3	-998,3	-1256,3	-1264,7	-1219,7
400° DRY	-1912,3	-2129,3	-1834,7	-2094,0	-2096,7	-2148,0

ULTRASONIC PULSE VELOCITY* (m/sec) MEASURED AFTER RE-IMMERSION IN WATER

TEST TEMPERATURE	CONCRETE MIXES			MORTAR MIXES		
	BCY	CCX	CCY	BMY	CMX	CMY
	C_1	C_2	C_3	M_4	M_5	M_6
70° SAT	-58,3	-12,7	-25,7	-58,3	-112,3	-41,7
100° SAT	-144,0	-85,0	-100,3	-211,0	-318,0	-284,0
70° DRY	-87,3	-163,0	-3,0	-94,0	-220,0	-107,0
100° DRY	-217,7	-240,7	-182,0	-438,0	-538,7	-473,3
150° DRY	-298,7	-307,0	-343,0	-596,7	-625,0	-551,7
250° DRY	-227,0	-173,3	-190,7	-558,0	-523,3	-439,7
400° DRY	-218,0	-256,7	-299,7	-224,3	-359,3	-450,0

* Mean coded value calculated from the coded values at test times (T + 36 hrs),(T + 36 hrs + 1 cycle) and (T + 36 hrs + 2 cycles).

TABLE A.V.3.6

POISSON'S RATIO* MEASURED AFTER COOLING

TEST TEMPERATURE	CONCRETE MIXES			MORTAR MIXES		
	BCY	CCX	CCY	BMY	CMX	CMY
	C_1	C_2	C_3	M_4	M_5	M_6
70° SAT	0,021	0,021	0,019	0,016	0,018	0,034
100° SAT	0,019	0,030	0,013	-0,007	0,018	0,024
70° DRY	0,002	-0,004	-0,033	-0,025	-0,110	-0,029
100° DRY	-0,022	-0,033	0,031	-0,056	-0,102	-0,100
150° DRY	0,007	-0,002	-0,008	-0,041	-0,136	-0,117
250° DRY	0,65	0,022	0,026	-0,077	-0,011	-0,010
400° DRY	0,069	0,102	0,093	-0,023	0,023	0,056

POISSON'S RATIO* MEASURED AFTER RE-IMMERSION IN WATER

TEST TEMPERATURE	CONCRETE MIXES			MORTAR MIXES		
	BCY	CCX	CCY	BMY	CMX	CMY
	C_1	C_2	C_3	M_4	M_5	M_6
70° SAT	0,008	0,022	0,019	0,007	0,007	0,025
100° SAT	0,009	0,025	0,030	0,016	0,009	0,002
70° DRY	0,001	0,027	-0,024	-0,004	-0,034	0,059
100° DRY	-0,011	-0,006	0,008	-0,008	-0,050	-0,029
150° DRY	0,011	-0,010	-0,004	0,019	-0,027	-0,020
250° DRY	-0,005	0,020	0,026	-0,001	0,021	0,022
400° DRY	0,018	0,081	-0,005	0,007	0,023	0,074

* Mean coded value calculated from the coded values at test times (T + 36 hrs) (T + 36 hrs + 1 cycle), and (T + 36 hrs + 2 cycles).

TABLE A.V.3.7